Developing a Solar Energy Industry in Egypt

by

Sherife AbdelMessih

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements of the Degree of

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ABSTRACT

This paper assesses Egypt's current energy infrastructure and its problems, the available solar energy resource, and the technologies required to harness this resource. After this assessment, an industry based on high utilization of solar energy; local manufacturing of solar technology; and research and development in solar energy disciplines is proposed in order to solve the energy challenges faced by the country and capitalize on new opportunities that can bring prosperity to the country. Analysis of the various solar energy technologies, shows that Fresnel Concentrated Solar Power technology is the most suitable solar technology to build an industry around in Egypt, because it has the lowest cost of producing electricity out of all solar energy technologies; the highest share of local manufacturing; and it is feasible to deploy and maintain in large scale power plants all over the country. At the end of the paper a case study is presented on Egypt's experience with parabolic trough technology throughout the last 100 years.

Thesis Supervisor: Alice H. Amsden
Title: Barton L. Weller Professor of Political Economy

Biographical Note

Sherife AbdelMessih is receiving his Bachelors of Science degree from the Mechanical Engineering Department at the Massachusetts institute of technology (MIT) in June 2009. During his time at MIT, Sherife was a teaching assistant at the Sloan school of management for the graduate level corporate entrepreneurship class taught in the Sloan Fellows and the Sloan MBA programs. Sherife was also an undergraduate researcher at the Mechanical Engineering Department, the Center for Energy and Environmental Research, the International Development Group, the Nuclear Engineering Department, the Department of Urban Studies and Planning and the Media Lab. He founded the MIT Egyptian Club in 2006 with the goal of representing Egyptian culture on campus, and creating a community for Egyptians at MIT and the Boston area. In addition, he also founded the MIT Future Forum which brings together the world's most revolutionary ideas to MIT.

Sherife is a recipient of the MIT Community Catalyst award, given to the 40 most influential leaders on campus; the MIT Public Service Fellowship, given to only 25 MIT students, and the Legatum Center for developmental entrepreneurship grant. He attended MIT as an Onsi Sawiris Scholar, a $300,000 scholarship.

Sherife developed vast entrepreneurial experiences through his involvement with startups in the Energy, IT, Finance, Entertainment and Management Training sectors over the last 4 years. He was also an advisor on the project to develop the first Solar Power Plant in Egypt and the Middle East. Over the last 3 years, Sherife has developed an innovative design of leadership and entrepreneurship programs, known as SPARK! The program is currently compromised of a leadership and business program for high school students, and an entrepreneurship program for college students.

Upon graduation Sherife is looking forward to playing a pivotal role in the development of a solar energy industry in Egypt. Other endeavors that he is excited about pursuing include developing the entrepreneurial ecosystem in Egypt. In addition, he is also working on designing next generation educational curriculums at the high school and university levels, with the goal of developing world class educational institutions in Egypt that will graduate generations of students capable of propelling the country into the developed world. Sherife is influenced by figures from the Renaissance generation such as Leonardo DaVinci; he has a deep passion for art, music, film and design.

Sherife is a citizen of the Republic of Egypt and is an enthusiast of Mediterranean culture. An avid athlete, he plays over 10 sports competitively and speaks fluent French, Arabic, English, in addition to holding a basic command of his indigenous Egyptian language.

Acknowledgments

I am very grateful to Orascom Construction Industries and the Onsi Sawiris Scholarship Foundation for financing the last four years of my undergraduate studies at MIT. In addition I would like to thank Orascom for inviting me to work on the project to construct the first solar power plant in Egypt and the Middle East in 2007.

Furthermore I want to thank the entire faculty that has taught me directly or indirectly during my time at MIT. I would like to thank Prof. Alice Amsden, my thesis supervisor for stimulating my interest in economic development and helping me understand the various factors that set countries apart with regards to how quickly they develop. I am also thankful to Prof. Val Livada for inviting me to be a teaching assistant at the Sloan School of Management for the graduate level corporate entrepreneurship class.

I would also like to thank the MIT Undergraduate Research Opportunity office for giving me the opportunity to explore my various research interests. I am also thankful to the MIT Public Service Center for providing seed funding for the first SPARK! program in the summer of 2007, which has become one of my strongest passions today. Finally I want to thank all my family and my friends for their continuous love and support, and God for his endless empowerment.

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Dedicated to my Heavenly Father for his Eternal Love

Chapter 1: Introduction

In Egypt, the sun has always been a vital source for the prosperity of the country. 5,000 years ago the ancient Egyptians understood the important role that the sun played in their daily lives and consequently they worshiped Ra, the sun god who was believed to rule the sky, the earth and the underworld. The ancient Egyptians also called one of their most ancient capitals Heliopolis, meaning 'the city of the sun'

Today the sun is still a vital source for many of Egypt's most affluent industries. The very popular Egyptian cotton and Egypt's agricultural industry would not be the same without the country's incredible solar resource along with other important factors. The country's all year round sunshine also enables tourists to visit the country and explore its history and culture in all four seasons. Consequently the sun's gift to Egypt has enabled the Egyptians to build many profitable industries such as agriculture and tourism which represent a very high percentage of the country's GDP.

However, Egypt is yet to build an energy industry that harnesses the abundant and free energy source that is available from the sun. In addition to generating electricity, current solar energy technologies can be used to provide fresh water by solar desalination processes and heat for industrial and residential heating processes. Indeed only 0.001% of all the desert in Egypt is needed to generate all of the country's electricity demand using currently available solar technologies. Moreover, one km squared of Egypt's desert can generate 165,000 meters cubed of fresh water per day from solar desalination [1].

But Egypt does not have the industry to enable it to capitalize on this extremely valuable resource. Two critical factors that must be in place for the successful creation of an industry are the technical know-how required to build the industry and the right policies required to support the creation of the industry in its early stages. This paper focuses on the technical know-how factor required to build the solar energy industry in Egypt and acknowledges that right policies will also have to put in place to support the development of a new solar energy industry in the country.

We will start by exploring some of the opportunities that a solar energy industry in Egypt can capitalize on and some of the problems it can solve. In this section we will also briefly mention the energy policy situation in Egypt to acknowledge the need for Egyptian policy makers to revaluate their energy policies in order to solve some of the energy challenges the country is facing and pave the way for a new solar energy industry. After establishing the need for a solar energy industry in Egypt, we will discuss what this industry will be compromised of and describe the different solar technologies that can play a role in this industry. Following that we will analyze the different solar technologies to determine which one is most suitable to build an industry around in Egypt. Finally a case study is presented on Egypt's successful and unsuccessful experience with one of the solar energy technologies.

Chapter 2: Why Does Egypt Need a Solar Energy Industry?

In this chapter we will investigate Egypt's current energy infrastructure by looking at the different types of energy sources used to meet the energy demand requirement. After we examine the supply and demand dynamics of each energy source, we will find that there is a need for a more stable and renewable energy resource.

After demonstrating this need, Egypt's renewable energy resources are assessed to determine which source is the most abundant in resource and which one has been used mostly in the past. We will then make a case for which of these renewable resources should Egypt focus its efforts in developing and utilizing in order to create a more renewable energy infrastructure.

Subsequently we will present an opportunity for exporting, large amounts of clean electricity generated from solar power plants in the deserts of Egypt, to the European continent. This is an opportunity that many European countries are pushing for in order to secure a less expensive and more stable energy supply for their very own future. In addition it has the potential to become a high percentage of Egypt's GDP because of the large revenues involved in the scale of this project. This opportunity can be capitalized on well if the country has the industry to deliver such a project.

Finally we will briefly visit the benefits that large scale solar energy power plants can provide by greening and utilizing the Egyptian desert, in addition to generating a large stream of revenues from carbon credits under the Kyoto Protocol.

2.1 Egypt's Current Energy Infrastructure

The majority of Egypt's current energy mix is compromised of natural gas and heavy oil for electricity generation, in addition, hydro power from multiple dams along the Nile River has a significant share, and wind energy has a very small share. For transportation the country depends on various qualities of petroleum products as vehicle fuel.

Oil

Egypt has been known to be a large producer and exporter of oil, yet when one looks at its production and consumption figures closely we realize that Egypt will become a net importer of oil in the near future and might run out of oil reserves in the next 30-40 years. Egypt had its oil production peak in 1995 when it was producing 950,000 barrels per day (bbl/day) of crude oil [2]. Since 1995 oil production has been falling steadily to reach 664,000 bbl/d in 2007 [3]. Keeping in mind that oil consumption was 653,000 bbl/d in 2007, we can see that the gap between production and consumption is getting smaller and thus Egypt is destined to become a net oil importer in the near future [4].

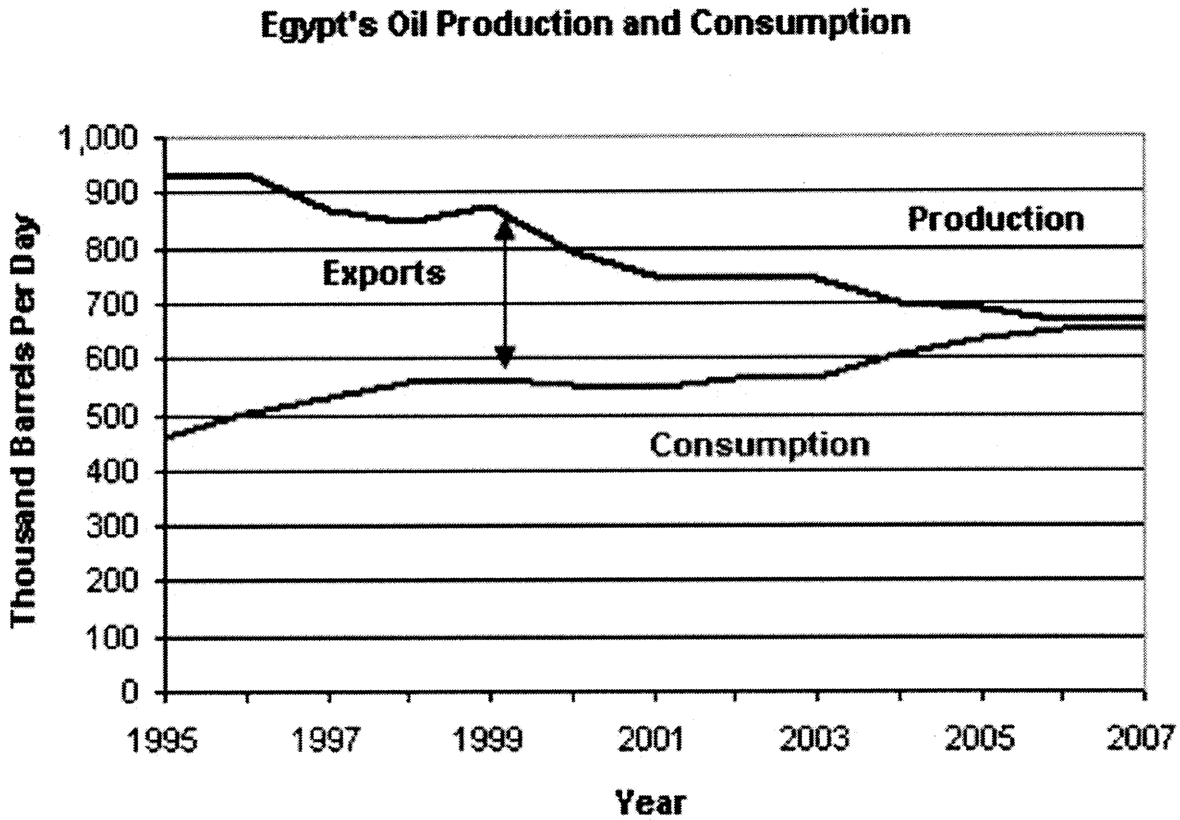

Figure 1: Egypt's oil production and consumption figures.

Source: Energy International Agency (EIA), August 2008

We can clearly see two problems from this scenario: increasing oil consumption and decreasing oil production. The rise in oil consumption is caused by an annual increase in the number of vehicles as a result of a rapidly increasing population. Egypt's population stands at 80 million people today and is increasing at a 1.8% annual rate [5]. To put things in perspective, Egypt's population in 1950 was 20 million people [6].

The main factor behind Egypt's falling oil production is the lack of new major oil discoveries and declining output in the existing oil wells. Most of the country's oil output today comes from four main areas: the Gulf of Suez, the Western Desert, the Eastern Desert, and the Sinai Peninsula. The Gulf of Suez region represents about 50% of production, and it is also the area that is decreasing most rapidly in production [7]. With regards to new major discoveries, the Saqqara field represents the last major find since 1989. It was discovered in 2003 by BP, came online in 2008 and is estimated to contain 80 million barrels [8]. Despite enhanced oil recovery techniques at mature fields, production is continuing to decline annually. Thus we can conclude that Egypt is in an urgent need for a different energy resource than oil.

Natural Gas

Egypt's natural gas reserves are in a better position than its oil reserves. In 2006 the country produced around 1.9 trillion cubic feet (Tcf) of natural gas and consumed 1.3 Tcf. The country's estimated proven reserves of natural gas are 58.5 Tcf [9].

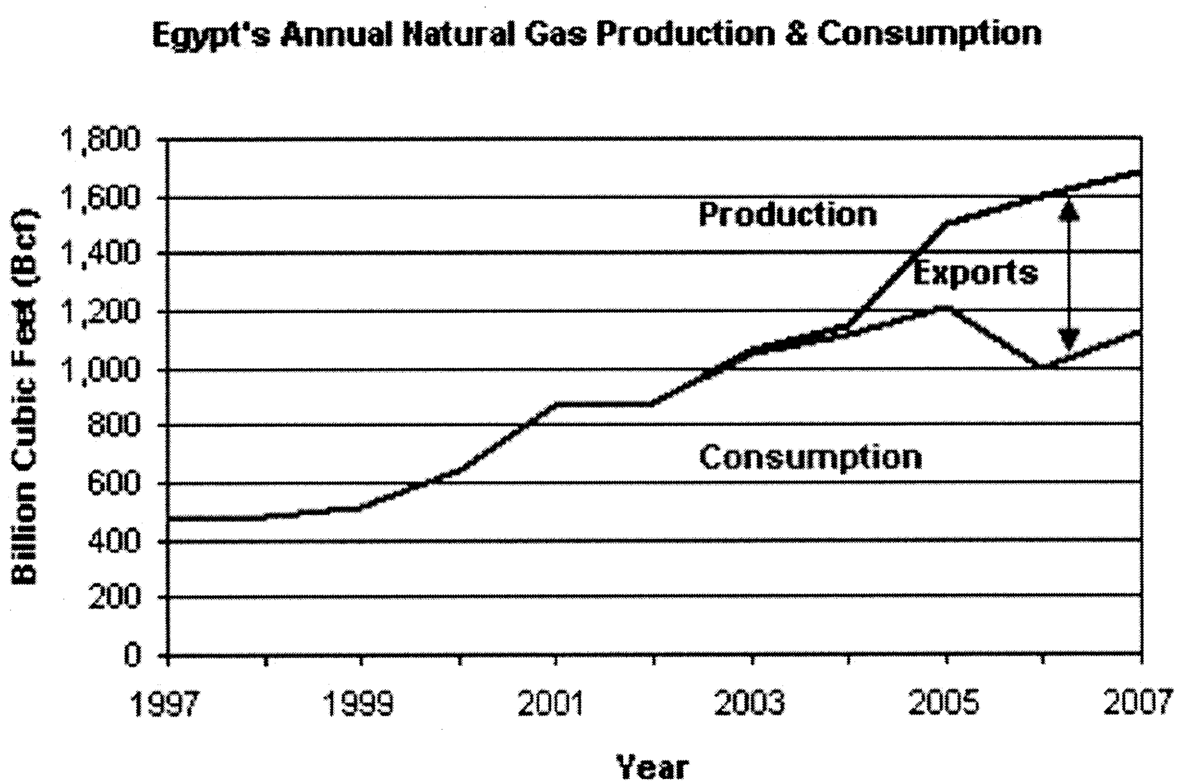

Figure 2: Egypt's production and consumption of natural gas

Source: EIA, August 2008

Although Egypt's production and consumption of natural gas looks stable at this point, we should keep into consideration how the shift of oil to natural gas will disrupt this dynamics. The country's strategy of replacing its oil consumption with natural gas can only help in the short term, as in the long term this will stress its natural gas resources and disrupt the healthy dynamics seen above.

Egypt has also been developing its natural gas export infrastructure in order to generate more revenues from exports of this product. In addition to better pipeline infrastructure with its neighboring countries, Egypt made a leap in 2005 when its first liquefied natural gas (LNG) export terminal came online. LNG is a technology that makes exporting natural gas by ship technically feasible and cost effective. LNG terminals turn the natural gas into a liquid, thus reducing its volume that would have otherwise been too big to carry a significant quantity of it on a ship. Today, Egypt is not a novice when it comes to LNG terminals, for instance SEGAS which is one of 3 LNG terminals in the country, was the largest single LNG plant in the world when it became operational in 2005 [10]. The terminal's current capacity is 5 million tons per year, and there are currently plans to expand the terminal's output to 10 million tons per year [11].

The reason Egypt's current LNG infrastructure is of importance to us is that it links the local prices of natural gas to the global ones. Egypt has been subsidizing its natural gas local prices at rock bottom prices since the very first years it produced the product. In 2008 the government was selling natural gas at a price of $0.75 per MBtu (Million British thermal unit) [12]. Today with the option of exporting natural gas to developed countries that have very high prices for this product, Egypt could save natural gas for export at higher prices instead selling it to the local market at subsidized very low prices. For instance, natural gas prices were at $13.31 per MBtu at the NY Mercantile Exchange Henry Hub in July 2008[13]. The figure below shows some global LNG prices that Egypt could be exporting at.

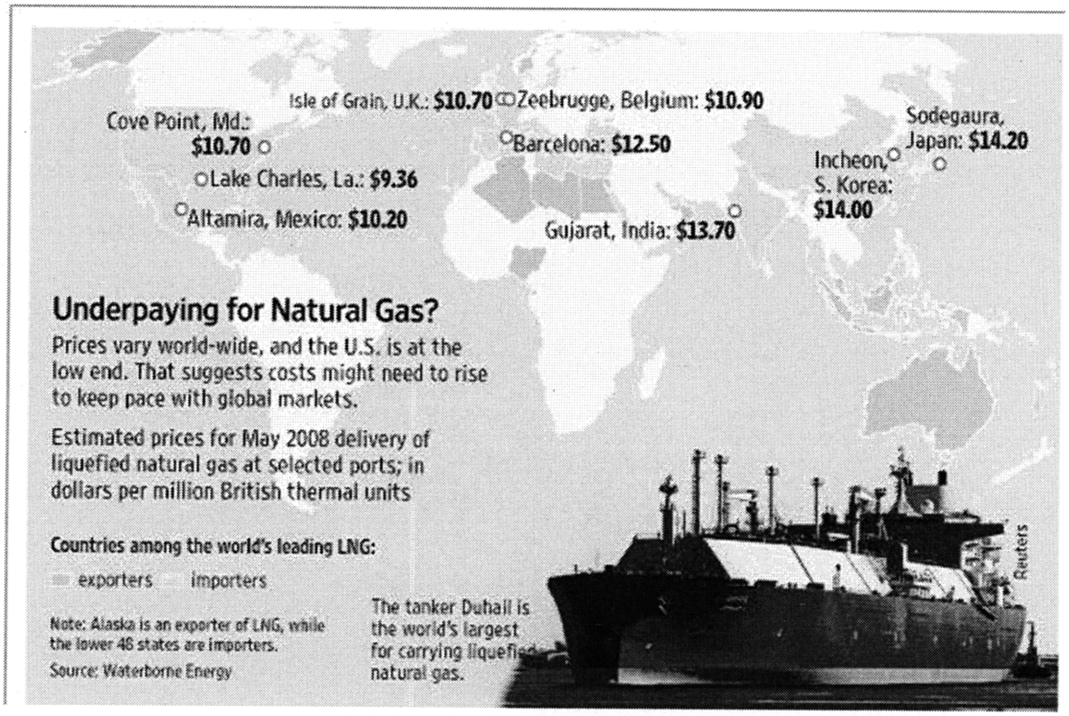

Figure 3: Some global LNG Prices. Source: Waterborne Energy

Thus, Egyptian policy makers must take into account the opportunity cost of heavily subsidizing natural gas, as every MBtu of subsidized natural gas could have been exported to Europe, Asia or America for much higher prices. Currently natural gas in Egypt is considered a very cheap fuel because it is abundant and cheap to produce. This scenario becomes false with the inclusion of LNG export terminals in the picture and the opportunity cost of not exporting. Thus policy makers must revise their assumptions and their assessment of the situation. If Egypt used a different fuel for electricity production it could be making additional billions of dollars in revenues from LNG exports to the rest of the world at high prices instead of selling it cheap locally.

Electricity Generation Infrastructure

In 2007 Egypt's electricity generation capacity stood at 22 GW and peak load reached 18.5 GW [14]. The ministry of electricity estimates that Egypt's demand for electricity will grow annually by 6.38% in its latest published annual report [15]. Consequently power plants are under construction to raise the country's generation capacity to 32 MW by 2010 [16].

To emphasize the rate at which energy consumption is growing in Egypt, in 2008 124.9 billion kWh were produced, an 8.23% higher than the 115.4 billion kWh produced in 2007 [17]. So demand for electricity is actually growing faster than the ministry had forecasted in 2007.

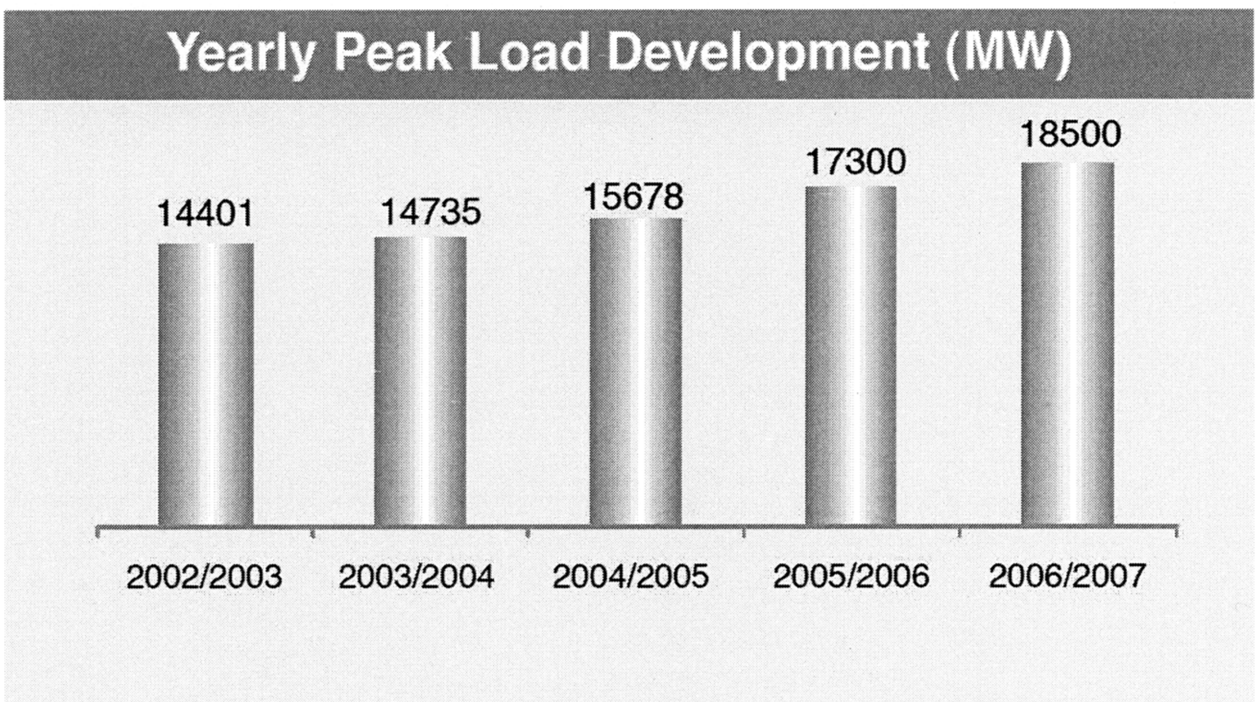

Figure 4: Growth in electricity peak demand in Egypt

Source: Egyptian Ministry of Electricity, Annual Report 2006-2007

As we can see in figure 4, most of Egypt's electricity generation comes from fossil fuel resources (thermal energy), followed by hydro power and wind energy.

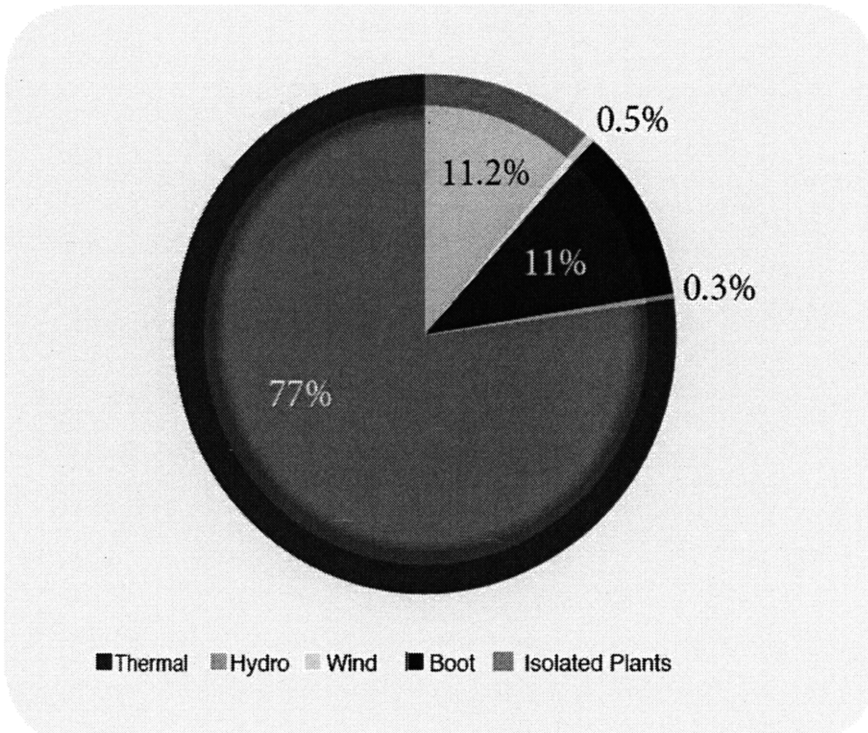

Figure 5: Egypt's electricity production mix (Thermal refers to fossil fuel resources, BOOT refers to plants not owned by the government, which also use fossil fuels, and isolated plants are plants that are not connected to the national grid)

Source: Egyptian Ministry of Electricity, Annual Report 2006-2007

Given that Egypt will always be building power plants in order to increase its electricity generation capacity to meet the annual 8.23% increase in demand, the majority of these power plants should use renewable energy resources that will not stress Egypt's supplies of natural gas and oil. In addition, since the ministry of electricity serves 22.6 million clients [18], renewable technologies like wind or solar should be utilized to bring electricity to people with no access to electricity since building new transmission lines is more expensive.

Conclusions

We have seen how Egypt is running out of oil resources, which will put a lot of stress on the country's natural gas resources. Given that 88% of Egypt's electricity generation is based on these two resources the country should not increase its share of fossil fuel based electricity generation and should instead build power plants with renewable energy based electricity generation to meet the 8.23% annual increase in demand. A transition into a renewable energy infrastructure in Egypt will allow the country to free up more natural gas for export and thus generate large revenues from the price difference between the local and global markets and meet energy demands without consuming limited resources like oil.

It is also worth mentioning that the Egyptian government's total energy subsidies for energy products stood at 60 billion Egyptian Pounds ($11 billion) in 2008 [19], an amount that is more than the government's health and education budgets combined. This is a huge burden on the financial resources of a government that is already stressed to meet the needs of a population growing at a rapid rate. Since these subsidies greatly reduce the price of fossil fuel based electricity, unsubsidized renewable electricity would be more expensive than subsidized fossil fuel electricity. By leaving their policies as they are, the Egyptian government would be shooting itself in the foot since their total subsidy expenses would be increasing as a result of an increasing demand for energy and renewable resources will not be able to compete with fossil fuel energy sources that are subsidized at rock bottom prices.

Therefore Egyptian policy makers must reconsider their subsidy policies for fossil energy resources by either reducing these subsidies or creating new policies and phased out subsidies that will support the use of renewable energy resources

2.2 Which Renewable Energy Resource Should Egypt Capitalize On?

After establishing the need to increase utilization of renewable energy in Egypt in the last chapter, we will now focus our attention to determining which renewable resource the country should capitalize on. In this chapter we will assess multiple renewable energy resources available in Egypt, and then we will compare the most suitable two to determine which one should be focused on.

Although the solar energy resource is most abundant renewable energy resource in Egypt, followed by hydro and wind resources; as we can see from the figure below, the Egyptian government has focused on wind energy and hydro energy as renewable resources in the last five decades, leading to a total of 375 MW of wind energy and 2783 MW of hydro energy installed today [20][21].

	Hydro		Geo		Bio		CSP		Wind		PV		Wa/Ti	
	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.	Tech.	Econ.
Egypt	80.0	50.0	n.a.	25.7	n.a.	15.3	73656	73656	7650	90.0	n.a.	36.0	n.a.	n.a.
	well documented resource taken from literature		from 5000 m temperature map considering areas with T>180°C as economic		from agricultural (bagasse) and municipal waste and renewable solid biomass potentials		from DNI and CSP site mapping taking sites with DNI > 2000 kWh/m²/y as economic		from wind speed and site mapping taking sites with a yield > 14 GWh/y and from literature (EU)					

Figure 6: Electricity generation potential from renewable energy resource in TWh/year (PV and CSP are two different solar energy technologies that will be discussed later)

Source: German DLR, MED-CSP Study

The buildup of hydro energy started in the 1960's during the cold war when Egypt received financing from the USSR for its first hydro dam, at this time wind and solar energy were not as economic as they are today. The transfer of know how in building hydro dams that occurred after the first project was completed allowed the country to increase its utilization of this technology.

However, the number of dams that can be built in the Nile River is obviously very limited as we can see from figure 6.

Although the benefits of solar outweigh those of wind energy in Egypt, the Egyptian government has set a goal to reach 20% renewable energy by 2020 and chose wind and hydro as the technologies that will achieve those goals [22]. In order to encourage the private sector to participate in this, the government has issued a law allowing a feed in tariff for wind energy. This means that if anyone owns a wind park and is generating a surplus of electricity they can sell this surplus to the government through the grid at the tariff rate which is usually higher than generation costs. The government has not set the tariff rate yet.

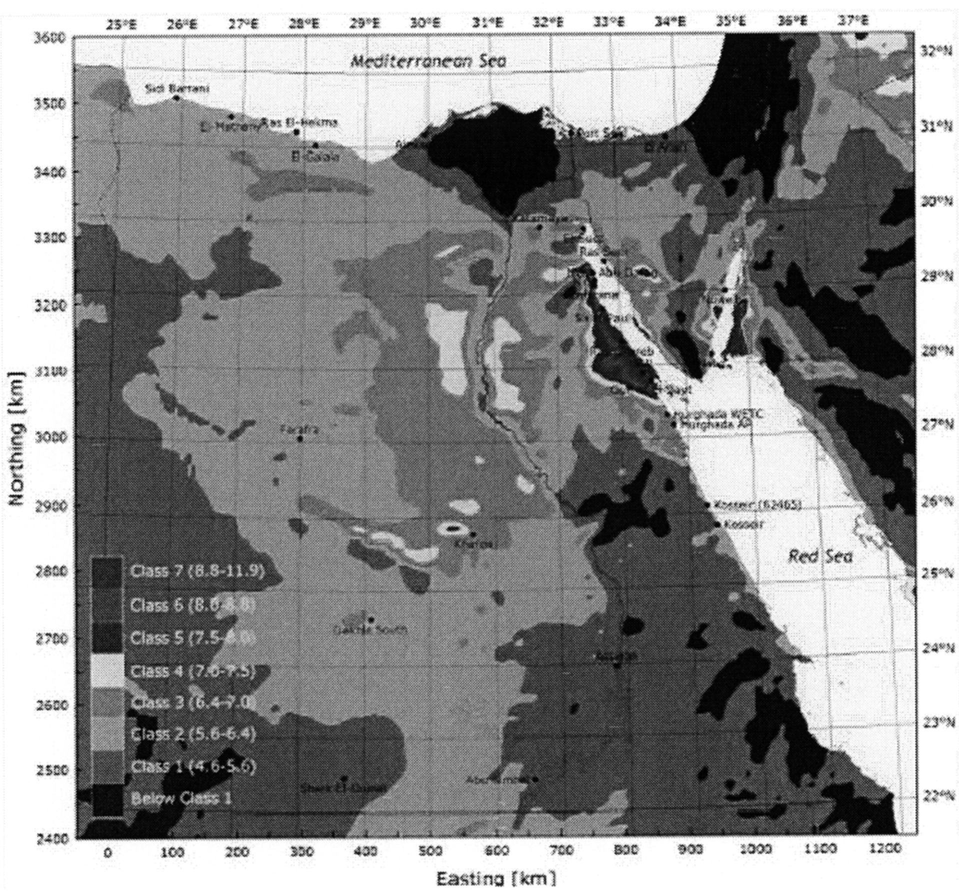

Figure 7: Wind atlas of Egypt, speeds in m/s Source: New & Renewable Energy Authority (NREA), Egyptian Ministry of Electricity

Egypt started building its first wind park in the last two decades, at this time and until today electricity generated from wind turbines was cheaper than electricity from solar. These wind parks were built in Zaafarana, Egypt overlooking the Gulf of Suez of the Egyptian Red Sea. An area that enjoys the highest wind speeds in the MENA region. Although on a small scale wind projects are cheaper to build than solar projects, wind energy in Egypt cannot provide the scale that solar can in Egypt. From figure 6 we see that economic electricity generation from wind energy in Egypt is 90 TWh per year while solar is a stunning 73,692 TWh per year. To put things into perspective, Egypt's electricity consumption was 124.9 TWh/yr in 2008 and is expected to be 630 TWh in 2050 [23], clearly only the solar resource can keep up with this demand. Since our intention is to build an industry, we need to pick the technology that can scale up with the industry and in this case that technology is solar.

In addition, since Egypt's peak demand for electricity occurs at the times of the day where the suns is very strong and during the summer season where electricity demand is 20% higher than the winter, these are the same times when the solar energy generation is at its peak because . This coupling of peak demand meeting peak generation can only happen with solar energy and not wind.

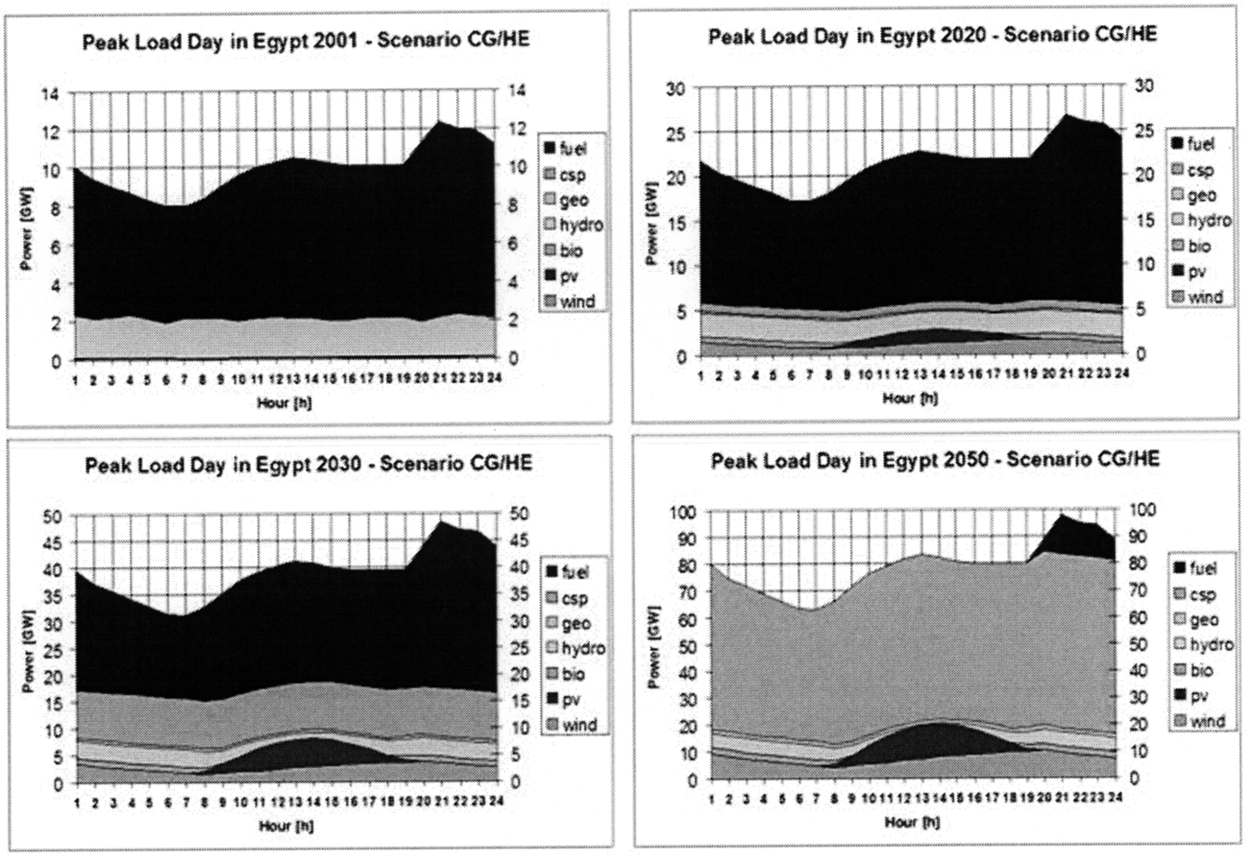

Figure 8: Different energy sources covering peak load scenarios in Egypt

Source: German DLR, MED-CSP Study

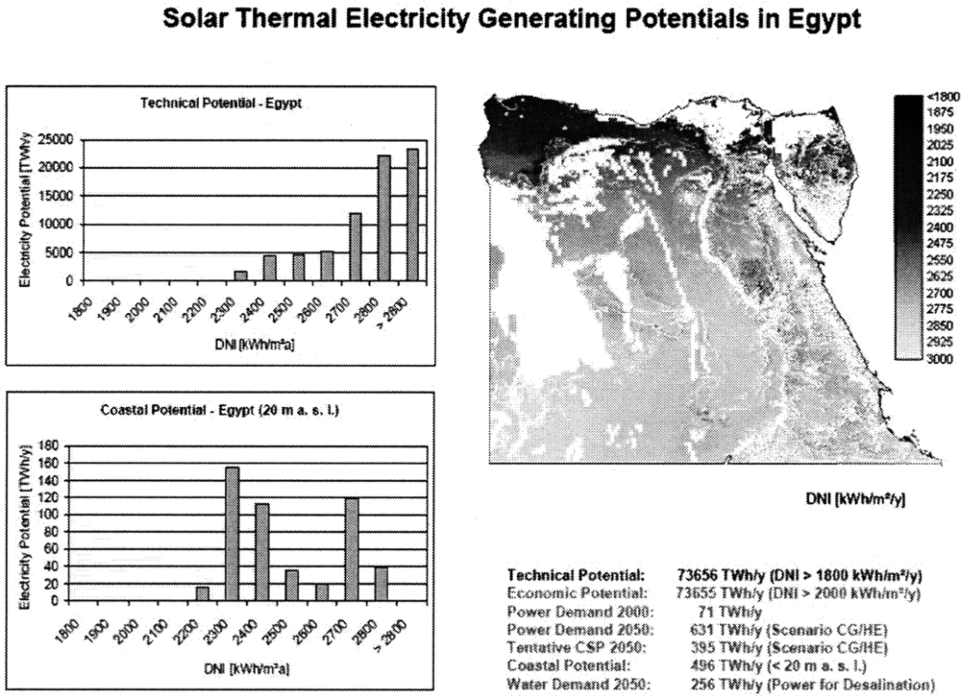

Figure 9: Electricity generation potential from CSP in Egypt

Source: German DLR, MED-CSP Study

It should also be noted that most of Egypt's power plants employ steam turbines which is the same turbine technology that large scale Concentrated Solar Power (CSP) technologies employ. This means that if we decide to make use of the existing infrastructure we can run CSP in hybrid operation with most of the power plants in Egypt instead of building solar power plants from scratch. Since we can use the existing steam turbines instead of building new ones, this greatly reduces the investment required for using solar power. This can allows us to operate on solar mode in the morning and burn fossil fuel at night, an incredible advantage that is only possible with solar technologies

Comp.	Station		No. of Units	Installed Capac. (MW)	Fuel	Commissioning Date
Cairo	Shoubra El-kheima	(ST)	4×315	1260	N.G-H.F.O	84 - 85 - 1988
	Cairo West	(ST)	4× 87.5	350	N.G-H.F.O	66-1979
	Cairo West Ext.	(ST)	2× 330	660	N.G-H.F.O	1995
	Cairo South 1	(CC)	3×110+4×60	570	N.G-H.F.O	57-65-1989
	Cairo South II	(CC)	1×165	165	N.G	1995
	Cairo North'	(CC)	4*250+2*250	1250	N.G-L.F.O	2006-2005
	Wadi Hof	(G)	3×33.3	100	N.G-L.F.O	1985
East Delta	Damietta	(CC)	6×132+3×136	1200	N.G-L.F.O	1989 – 1993
	Ataka	(ST)	2×150+2×300	900	N.G-H.F.O	85-86-1987
	Abu Sultan	(ST)	4×150	600	N.G-H.F.O	83-84-1986
	Shabab	(G)	3×33.5	100	N.G-L.F.O	1982
	Port Said	(G)	2*23.96+1*24.6	73	N.G-L.F.O	77-1984
	Arish	(ST)	2×33	66	H.F.O	2000
	Oyoun Mousa	(ST)	2×320	640	N.G-H.F.O	2000
	Sharm El-Sheikh	(G)	2×23.7 +4×24.27 +4×5.8 + 2×5	178	L.F.O	-
	Hurghada	(G)	3×23.5 + 3×24.3	143	L.F.O	-
	Zafarana(wind)'		105×0.6+117*0.66 +100×0.85	225	Wind	2000-2003-2004-2006
	Boot Suez Gulf	(ST)	2×341.25	682.5	N.G-H.F.O	2002
	Port Said East	(ST)	2×341.25	682.5	N.G-H.F.O	2003
Middle Delta	Talkha	(CC)	8*24.72+2*45.95	290	N.G-L.F.O	79-80-1989
	Talkha 210	(ST)	2*210	420	N.G-H.F.O	93-1995
	Talkha 750'	(CC)	2*250+1*250	500	N.G-L.F.O	2006
	Nubaria'	(CC)	4*250+2*250	1500	N.G-L.F.O	2005-2006
	Mahmoudia	(CC)	8*25+2*58.7	317.4	N.G-L.F.O	83-1995
	Mahmoudia''	(ST)	1*50+1*25	75	N.G-L.F.O	81-1982
West Delta	Kafr El-Dawar	(ST)	4×110	440	N.G-H.F.O	80-84-1986
	Damanhour Ext	(ST)	1×300	300	N.G-H.F.O	1991
	Damanhour (Old)	(ST)	3×65	195	N.G-H.F.O	68-1969
	Damanhour	(CC)	4×24.62+1×58	156.5	N.G-L.F.O	1985-1995
	El-Seluf	(G)	6×33.3	200	N.G-L.F.O	81-82-83-1984
	El-Seluf	(ST)	2*26.6+2*30	113	H.F.O	61-1969
	Karmouz	(G)	1×11.37 +1×11.68	23.1	L.F.O	1980
	Abu Kir	(ST)	4×150+1×311	911	N.G-H.F.O	83-84-1991
	Abu Kir	(G)	1×24.27	24.3	N.G-L.F.O	1983
	Sidi Krir 1.2	(ST)	2 ×320	640	N.G-H.F.O	99-2000
	Matrouh	(ST)	2×30	60	N.G-H.F.O	1990
	Boot Sidi Krir 3,4	(ST)	2 × 341.25	682.5	N.G-H.F.O	2002
Upper Egypt	Walidia	(ST)	2×312	624	H.F.O	92-1997
	Kuriemat1	(ST)	2×627	1254	N.G-H.F.O	1999-1998
	Kuriemat 2'	(CC)	2*250+1*250	500	N.G-L.F.O	2007
	Assiut	(ST)	3×30	90	H.F.O	1966 - 1967
Hydro Plants	High Dam		12×175	2100	-	1967
	Aswan Dam I		7×46	322	-	1960
	Aswan Dam II		4×67.5	270	-	85-1986
	Esna		6×14.28	86	-	1993
	Naga Hamadi		3×1.8	5.4	-	1997

Figure 10: Type of turbine technology current power plants in Egypt use; power plants marked (ST) or (CC) employ a steam turbine and thus can be run in hybrid efficiently with Concentrated Solar Power (CSP) Technologies

Source: Egyptian Ministry of Electricity Annual Report 2006/2007

Perhaps the government chose wind over solar because it is a bit cheaper today, yet we have shown in our analysis that solar is more suitable for the structure and dynamics of the energy market in Egypt and that costs will decrease beyond those of wind as we scale up and follow the learning curve.

2.3 Solar Electricity: Egypt's Future Largest Export Commodity

In this section we will discuss a European initiative that presents an invaluable opportunity to Egypt in particular and the Middle East and North Africa (MENA) region in general. This initiative envisions exporting electricity to Europe generated from hundreds of solar energy power plants in Egypt and the MENA region. We will present an overview of this scenario, its feasibility and motivation in addition to the benefits it can bring to Egypt.

Concerned with the effect of fossil fuels on climate change and the drastic consequences it could have on our world; countries of the European Union (EU) are seeking to transition into clean and renewable energy resources. Other factors motivating this include volatile fossil fuel prices and the need for a secure and abundant energy resource. Consequently, the German Aerospace Center (DLR) lead 3 studies between 2004 and 2007 to evaluate the potential of renewable energy in the MENA region; the expected need for power and water between now and 2050 in the EU-MENA region; and the feasibility of constructing an electricity transmission grid connecting the EU and MENA. These studies were commissioned by the German Federal Ministry for the Environment and the German Nature Conversation and Nuclear Safety (BMU), and are referred to as 'MED-CSP', 'AQUA-CSP' and 'TRANS-CSP' respectively.

The DLR studies have shown that, less than 0.3% of the entire unused desert area of the MENA region can provide enough electricity and desalinated seawater through Concentrated Solar Power (CSP) technology to meet the growing needs of Europe and the MENA countries. In addition, the studies also showed that Egypt's desert land is the most cost efficient location in the MENA region for these solar power plants to be built. It calculated that an area the size of Lake Nasser, seen in figure below can produce enough solar energy, equivalent to the whole Middle East's oil production [24].

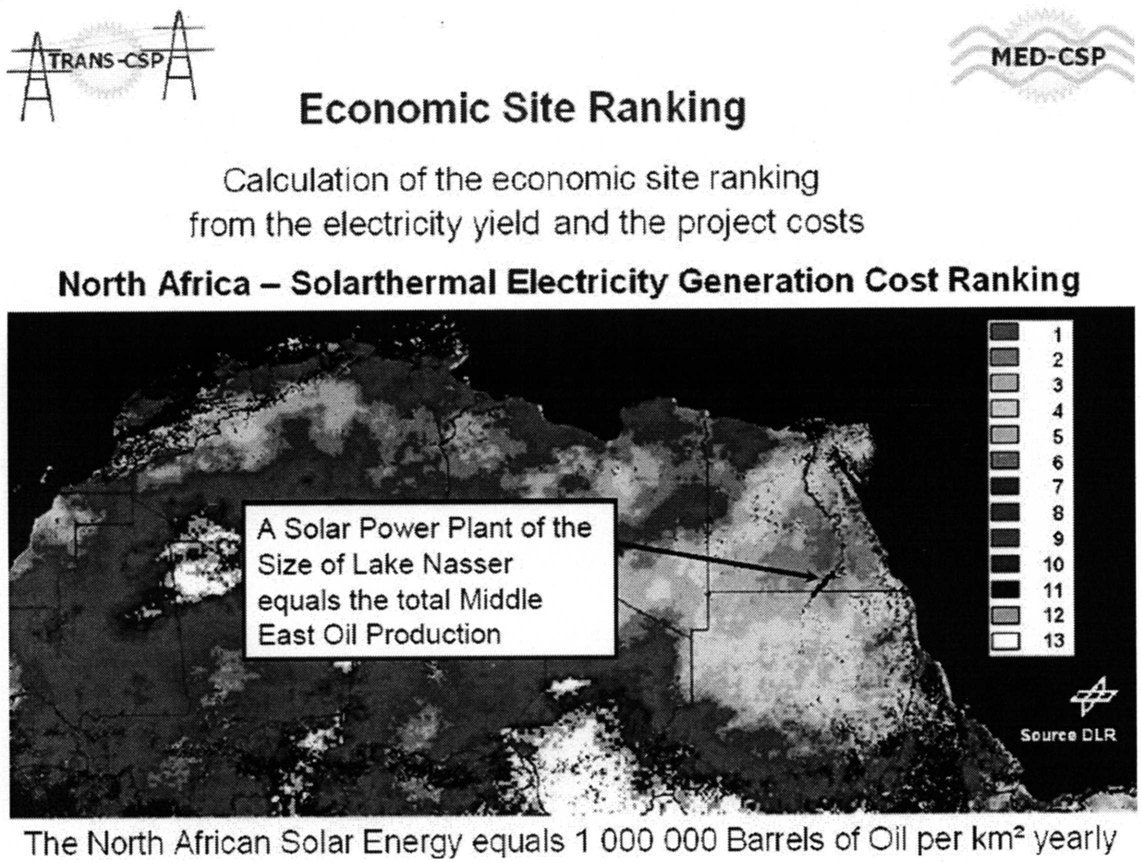

Figure 11: economic ranking of solar sites

Source: German DLR, MED-CSP Study

With regards to the EU-MENA grid, the study has shown that High Voltage Direct Current (HVDC) technology would make this feasible. HVDC transmission lines would limit loss of power during transmission to only 3% per 1000 km. Although there would be transmission losses up to 15% between Egypt and Europe, they are more than offset by the fact that levels of solar radiation in Egypt are about twice what they are in southern Europe. Furthermore there is much less seasonal variation in levels of sunshine in Egypt than there is in Europe [25].

Building large scale HVDC transmission lines is already feasible since up to 3 GW capacity have been deployed over long distances by ABB and Siemens for many years. The latest big project was in July 2007 when Siemens started building a 5 GW HVDC System in China [26]. The study calculated that electricity generated by very large scale CSP power plants in Egypt can cost as low as 4 euro cents per kWh and cost an additional one euro cent per kWh to transmit to Europe via HVDC lines, giving a total cost of 5 euro cents per kWh for imported solar electricity [27].

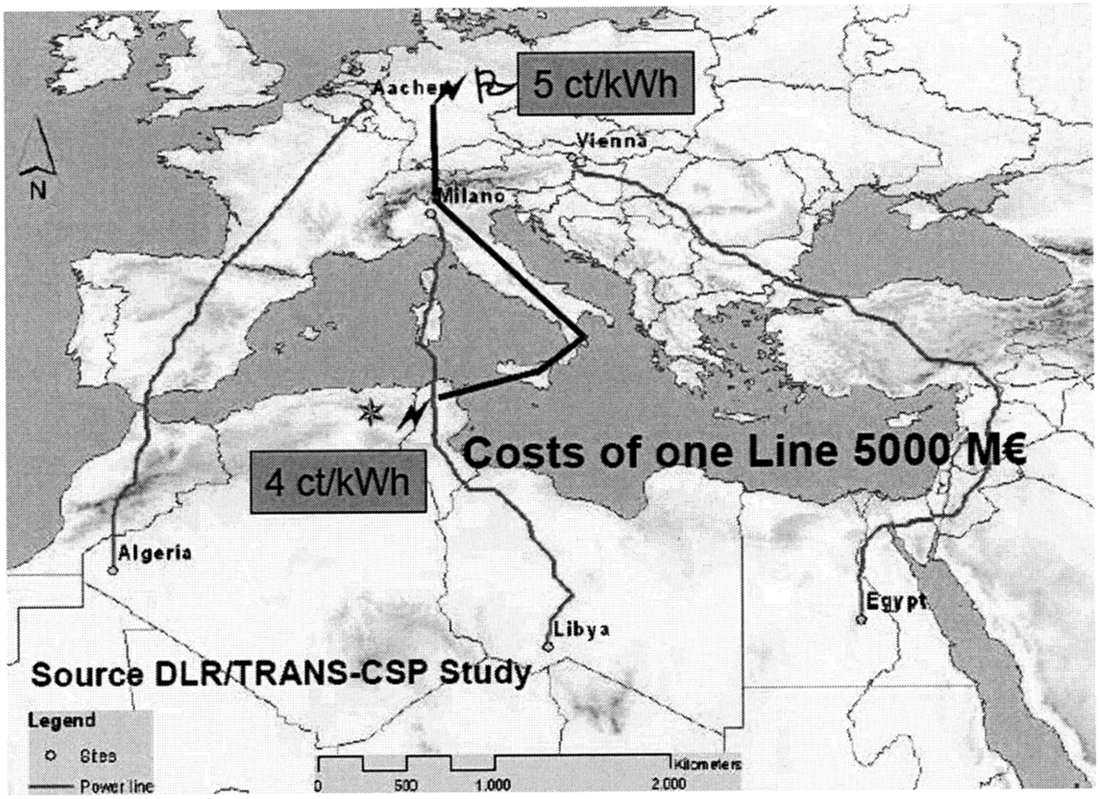

Figure 12: HVDC Transmission routes from North Africa to Europe and their costs

Source: German DLR, TRANS-CSP Study

The results of these studies have led the Europeans to pursue an ambitious goal of establishing a capacity of 100 GW of exportable solar power in MENA [28]. In coordination with the authors of the above papers, the DESERTEC foundation is now pushing for this initiative. The DESERTEC foundation is an initiative of the Club of Rome, a European based think tank of very influential global figures. DESERTEC was founded with the goal of providing clean and cost efficient energy for EU-MENA region as soon as possible, based on economic cooperation between the countries in the region [29]. A scenario of the grid that is being proposed by DESERTEC can be seen in figure 13.

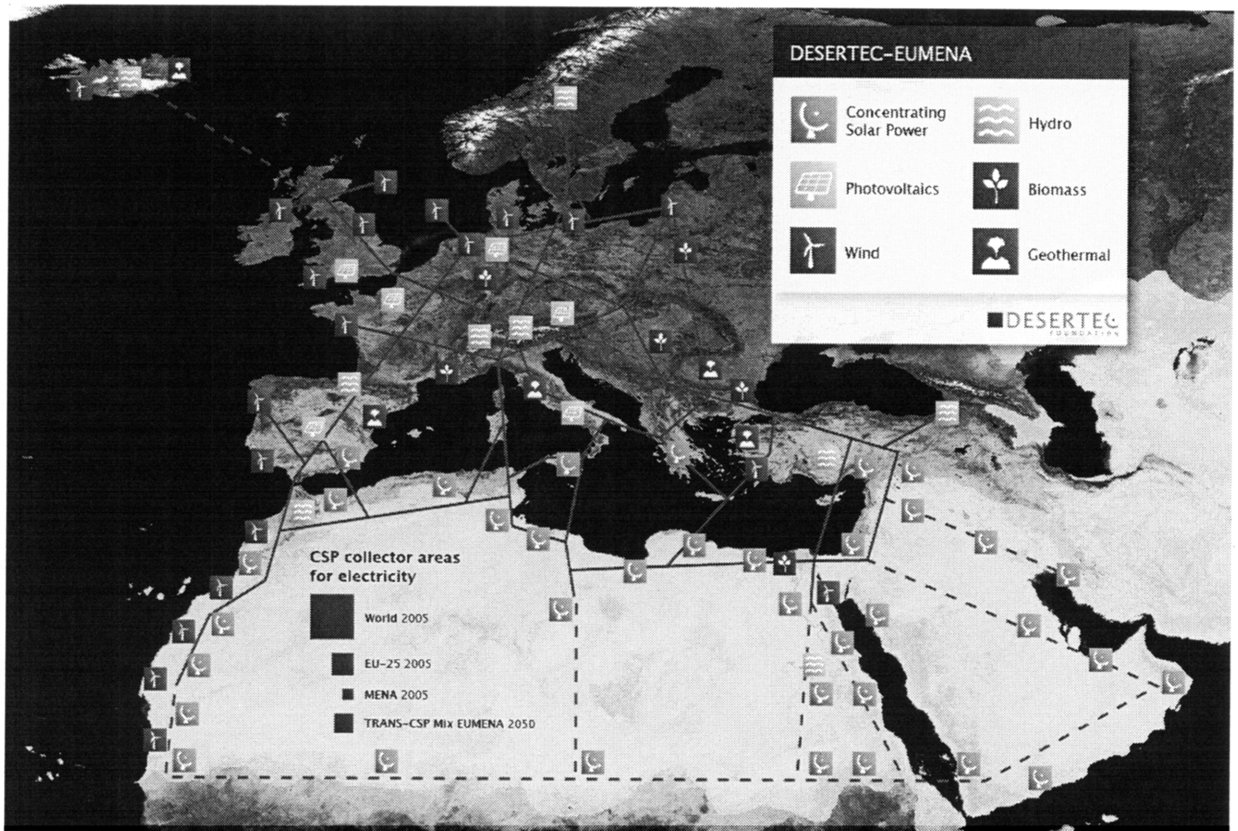

Figure 13: Areas of the size as indicated by the red squares would be sufficient for Concentrating Solar Thermal Power Plants to generate as much electricity as is currently consumed by the World (17,000 TWh/y), by Europe (EU-25, 3,200 TWh/y) and by MENA (600 TWh/y). respectively. The square labeled "TRANS-CSP Mix 2050" indicates the space needed for solar collectors to supply the needs for seawater desalination and about two-thirds of the electricity consumption in MENA in the year 2050 and about one-fifth of the European electricity consumption by Concentrating Solar Thermal Power Plants (2,940 TWh/y in total).Source: DESERTEC Foundation

This European initiative presents a gigantic opportunity for Egypt, according to the European plan, Egypt could be exporting up to 3.8 billion Euros worth of solar electricity in 2020 and up to 35 billion Euros worth of solar electricity in 2050 [30]. There are two different scenarios in which this could happen, the first is the status quo where the European companies will design, build and supply components for the solar power plants then Egypt will only earn a profit margin in exporting solar electricity to Europe. While the second is Egypt has a solar energy industry in place that will allow it to earn revenues in designing, building and supplying components for the power plants and then earning more revenues from selling solar electricity to Europe. The table below presents the details of this opportunity.

Year	2020	2030	2040	2050
Transfer Capacity in GW	2 x 5= 10	8 x 5= 40	14 x 5= 70	20 x 5= 100
Electricity Transfer in TWh/year	60	230	470	700
Capacity Factor	0.60	0.67	0.75	0.80
Turnover in Billion Euros per year	3.8	12.5	24	35
Land Area of CSP Plants in km x km	15x15= 225	30x30= 900	40x40= 1600	50x50= 2500
Land Area of HVDC Transmission lines in km x km	3100x0.1= 310	3600x0.4= 1440	3600x0.7= 2520	3600x1.0= 3600
Investment in Billions of Euros for CSP plants	42	143	245	350
Investments in Billions of Euros for HVDC transmission lines	5	20	31	45
Electricity costs in Euros per kWh for CSP plants	0.050	0.045	0.040	0.040
Electricity Costs in Euros per kWh for HVDC transmission lines	0.014	0.010	0.010	0.010

Figure 14: Main indicators of a EUMENA High (HVDC) interconnection for importing clean power from 2020 – 2050 according to the TRANS-CSP scenario (data 2006). In 2050, lines with a capacity of 5 GW each will transmit about 700 TWh/y of electricity from 20-40 different locations in the Middle East and North Africa to the main centres of demand in Europe. Source: DESERTEC Foundation 2006

This European initiative is an extremely lucrative opportunity for Egypt, which the country can completely benefit from by developing its own solar energy industry. Egypt should thus adopt an insistent role in acquiring competence and know how in solar energy technologies so that it can make the most of the unlimited solar resource available and the gigantic European solar electricity export opportunity. By doing so Egypt would create hundreds of thousands of jobs through a new industry, energy and water from desalination for its own people and billions of dollars from exporting clean solar energy to the European market. Moreover the trillions of kWh of clean electricity that will be produced can generate additional revenues by selling free carbon emission permits under the Kyoto Protocol.

In addition to all these benefits, CSP power plants can also utilize and green the uninhabited Egyptian deserts which represent 93% of the country's land. Waste heat from CSP power plants can be used to desalinate water and thus the coastal areas of the Egyptian Red Sea and Mediterranean Sea could be rehabilitated and used for agricultural purposes.

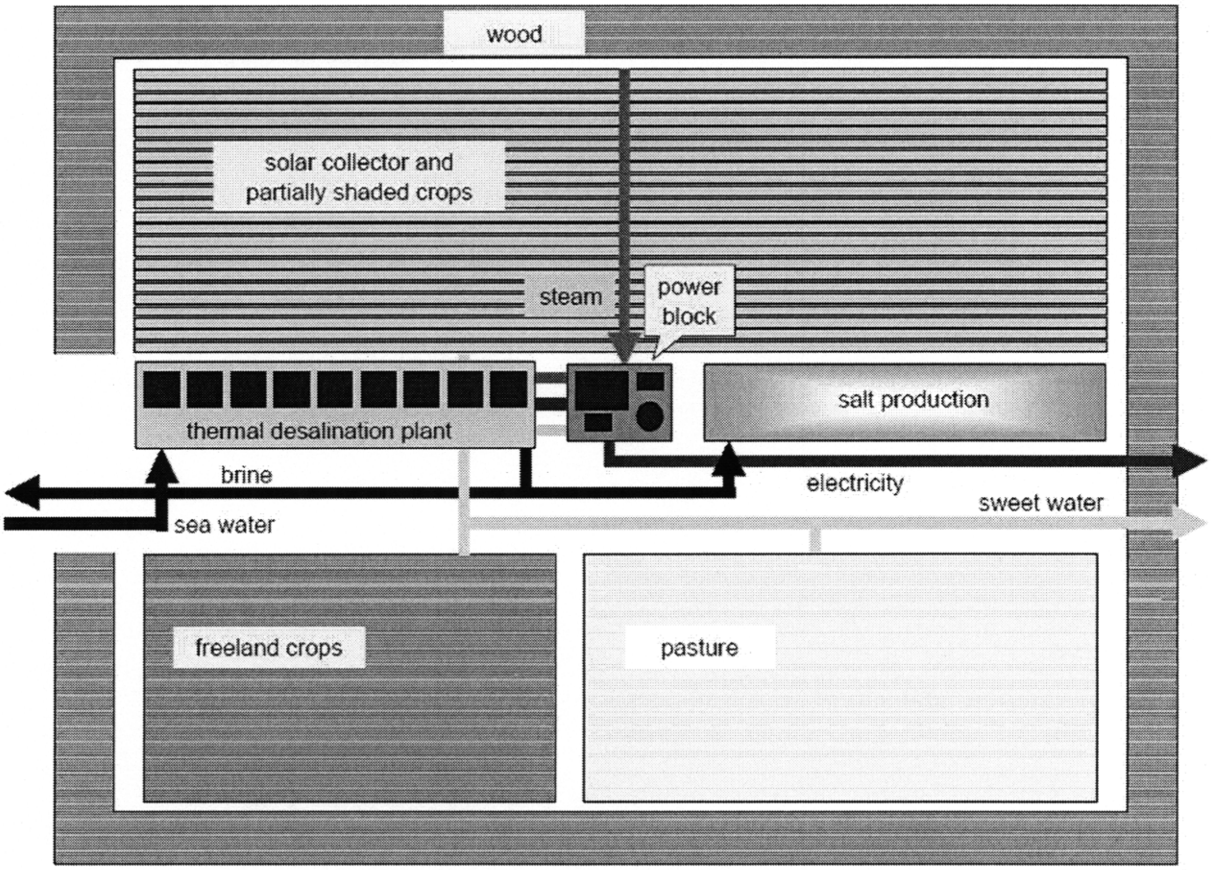

Figure 15: An example of a Concentrated Solar Power Plant generating heat to produce electricity and fresh water by desalination. Produced water can be used to grow crops in the desert

Source: Nokrashcy Engineering GmbH

2.4 Conclusions

In conclusion, we have shown in this chapter that Egypt must develop a solar energy industry to tackle the major challenges that it will be facing in the next decades. Having its very own solar energy industry will enable the country to free up more fossil fuels for exports at the high prices of the global market instead of selling them cheap in the local market; harness its most abundant energy resource to efficiently meet its rapidly growing energy and water demands and direct its exhausting energy subsidies budget to an industry that only needs them in its early stages instead of directing them to fossil fuels which require more subsidies every year.

In addition a solar energy industry in Egypt can become the country's largest export through the EU's interest in importing clean energy from the MENA region. The industry can also be the driver of the country's growth engine for creating jobs, revenues and development.

If Egypt does not create a solar energy industry it risks its future energy security and financial well being. In addition it will be missing on a humongous opportunity that could go to other MENA countries.

Chapter 3: What Makes Up a Solar Energy Industry?

After showing that it is absolutely essential to develop a solar energy industry in Egypt, we will now present what a solar energy industry is made up of. The context in which the phrase "needs to develop a solar energy industry" was used throughout the last chapter indicated that the author was referring to some combination of increased utilization and understanding of solar energy technology. In this chapter we will establish clearly what a solar energy industry is compromised of.

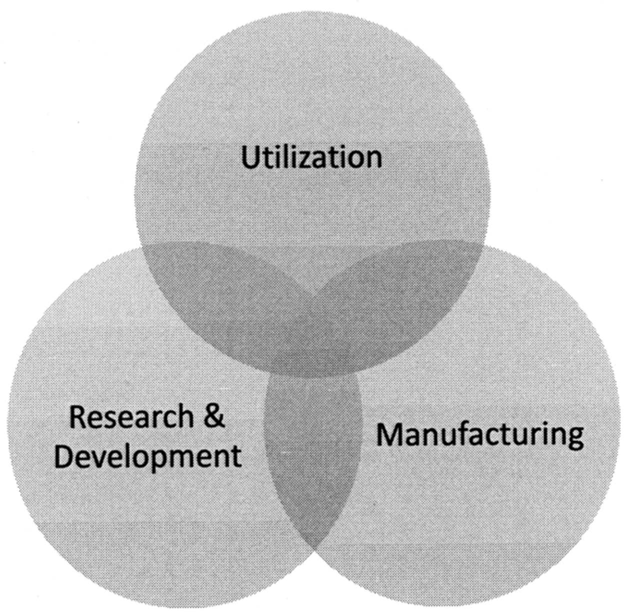

Figure 16: Author's definition of a Solar Energy Industry

The author defines a developed solar energy industry as the aggregate of high utilization of solar energy technology, manufacturing capability of solar energy technology and involvement in research and development activities to make better solar technologies. This is what the author refers to when the subject of developing a solar energy industry in Egypt is brought up.

Currently Egypt's involvement with solar energy is compromised of some scattered academic research at universities, some companies involved in selling imported solar energy technologies and the closest it gets to manufacturing is basic assembly of some solar energy technologies whose components were imported. Clearly, there is no solar energy industry in Egypt of the type the author is referring to. In order to get a better idea of what a solar energy industry looks like, we will briefly examine the German solar energy industry.

The German solar energy industry turnover has risen within the last six years from around 450 million Euros to some 4.9 billion Euros. The companies in the industry have been investing 500 million Euros annually in the construction, expansion and modernization of their solar factories in order to increase their production capacities. The number of people employed in the industry had risen to around 50,000 in 2006 [31].

On the utilization side, Germany had 5.337 GW of Solar PV technology installed in 2008, that's 35% of the world's total PV installation [32]. On the manufacturing side, there are over 40 companies that manufacture solar PV panels in Germany [33]. In addition, the world's leading suppliers of Concentrated Solar Power (CSP) technology are also in Germany. Moreover, most if not all, of the companies manufacturing solar technology in German have their own R&D divisions in addition to the various independent R&D labs specialized in solar technologies.

Furthermore, the services and products of the German solar energy industry include planning, construction, equipment, systems engineering, operation, monitoring, finance packages and training. In addition to this, there are providers of consulting services, such as technical consultation, feasibility studies, environmental impact studies, audits and measurement instrumentation.

Although Germany's geographical position on the world map does not make it the ideal location for solar energy because it only receives moderate levels of solar radiation, it has become the largest solar industry in the world. Germany has always been a pioneer in solar energy technologies, yet its large scale utilization of solar technology was predominantly encouraged by the 1990 Energy feed in law that set a stunning feed in tariff of up to 57.4 euro cents per kWh for solar generated electricity [34]. This feed in tariff attracted all world's biggest developers of solar technology to set up manufacturing plants in Germany.

One can see how large and strong the German solar energy industry is across all three of its divisions: utilization, manufacturing and research & development. It would take books to describe or list all the different members of the German solar energy industry. We can see from the figure below how Egypt's activities with solar energy are insignificant compared to the abundant solar resource it has.

	Germany	Egypt
Solar PV utilization	5,337 MW	15 MW
Solar thermal utilization	1,000,000 solar water heating units	500,000 solar water heating units
Solar PV manufacturing	Over 40 manufacturing companies	No manufacturing companies, 7 companies doing last stage assembly only
Solar Thermal manufacturing	- Design and manufacturing of solar thermal power plant components -Solar water heaters manufacturing	No manufacturing, 13 companies doing last stage assembly of solar water heaters only
Solar PV R&D	Very strong	Only one lab in partnership with IBM starting in 2010
Solar Thermal R&D	Very strong	Insignificant

Figure 17: Egypt's activities with solar energy compared to Germany

Source: Adapted from German Federal Ministry of Economics and Technology, Egyptian New & Renewable Energy Authority and authors fieldwork

Consequently, the Egyptian government must encourage solar energy utilization with the right set of policies as we have seen in the German example, in order to attract investments and talent that will develop the industry.

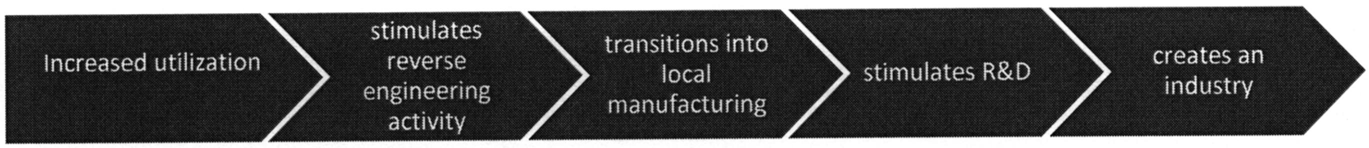

Figure 18: Effect of increased utilization of solar energy

Having showed that we need to build up a solar energy industry because there is little infrastructure, know-how and utilization in Egypt, we will now determine which solar energy technology the industry should be built around. Given that there are many solar technologies for different applications and that we are building a new industry it makes sense to focus on one technology in the beginning, in order to focus resources and generate results faster. We will present an overview of the different solar energy technologies for electricity generation in the next chapter and then we will analyze and choose the most appropriate technology for Egypt in the following chapter.

Chapter 4: Overview of Solar Energy Technologies

Solar technologies used for electricity generation can be classified into two categories: Photovoltaic (PV) and Concentrated Solar Power (CSP). In this section, we will briefly discuss the science, design, cost and stage of development of the various PV and CSP technologies. With this understanding we can determine which technology is most suitable to build an industry around in the next chapter.

4.1 PV Technology

A PV system consists of one or more PV modules, and each PV module consists of about 40 PV solar cells made from a material with special properties referred to as a semiconductor.

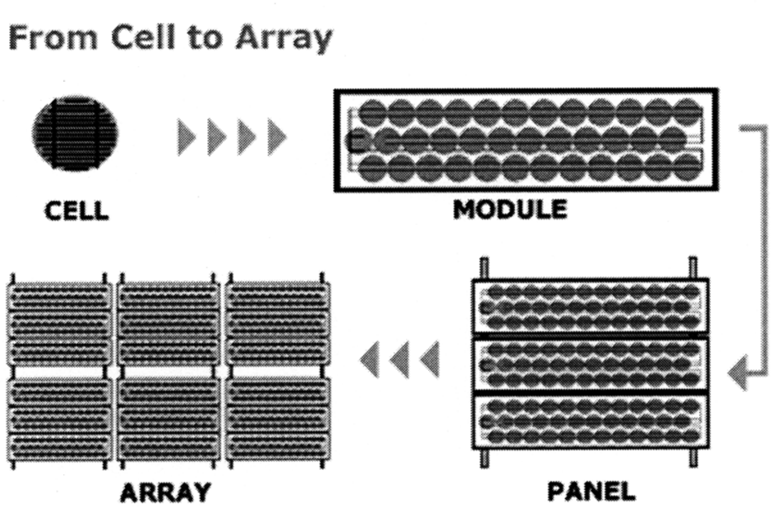

Figure 19: assembly process of PV components

Source: Solar Direct

The photovoltaic cell is the component responsible for converting light to electricity through the physics of the photo electric effect.

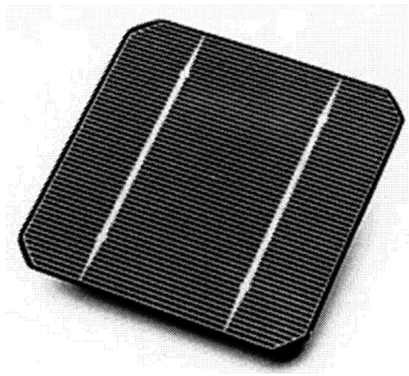

Figure 20: PV Cell Source: US Department of Energy

When sunlight strikes a photovoltaic cell, it absorbs light particles called photons which contain energy. The photon that the cell absorbs knocks an electron loose from a semiconductor material atom such as silicon which is used to produce a current. To be able to use the electric current generated from the PV cell, more components need to be added to form a PV system. PV systems are often compromised of a module, controller, battery, inverter, and cables.

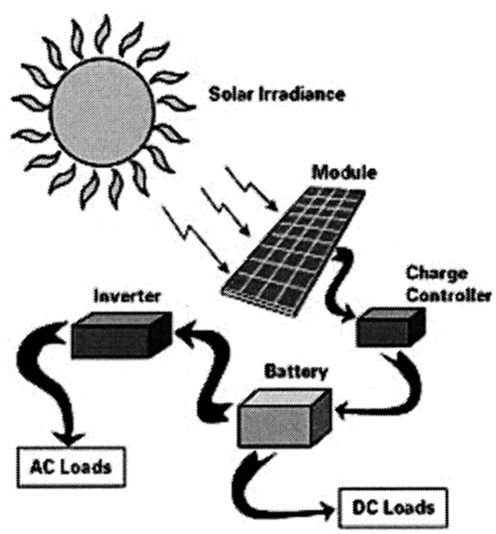

Figure 21: PV System Source: Sun Energy Facts

The first PV solar cell was created in the 1950's at Bell Laboratories, during the first decades of their production prices were as high as $200 per watt of electricity produced, therefore PV solar cells could initially be found only in space applications and small commercial applications such as toys, watches and calculators [35].

Today the price of PV solar module has decreased since its early days to reach an average price of $4.74 per watt [36]. However, the price of a PV system is higher than this because a system requires more components than modules to harness the electricity created by PV solar cells. Thus, the average cost for a residential PV system is between $7.5 and $9.5 per installed watt. Today the electricity cost from PV solar panels range between 20-50 cents per kWh and thus they are still very expensive when compared to traditional energy sources and even other solar energy technologies such as CSP [37].

Although PV is not currently the most cost effective solar technology, it is expected to continue decreasing in cost in the next decades as the technology benefits from economies of scale, more efficient manufacturing processes, more efficient cell architecture design and cheaper raw materials.

Even though PV is more expensive than CSP technologies it has found a market niche for roof installed solar systems. Most CSP technologies are cost efficient at large scales and so they are mostly used for large scale utility projects, whereas PV technology is more coming to be found in small scale energy systems such as residential installations on roof tops.

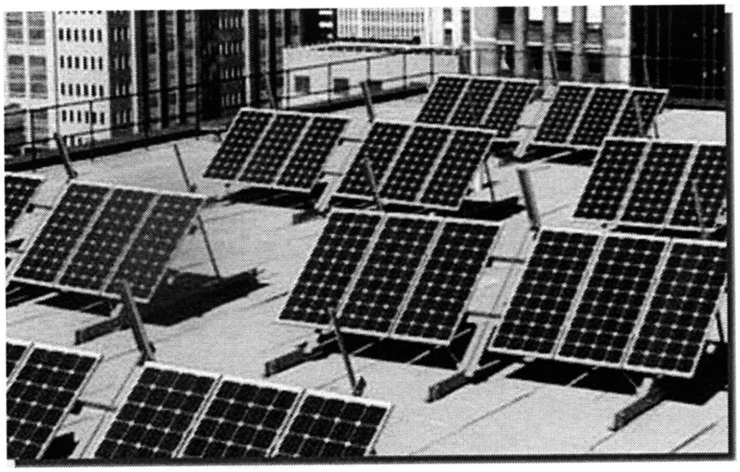

Figure 22: A roof mounted PV System Source: Solar Direct

In 2008, there were 5.95 GW of PV panels installed around the world, the majority of those being in Germany and Spain [38].

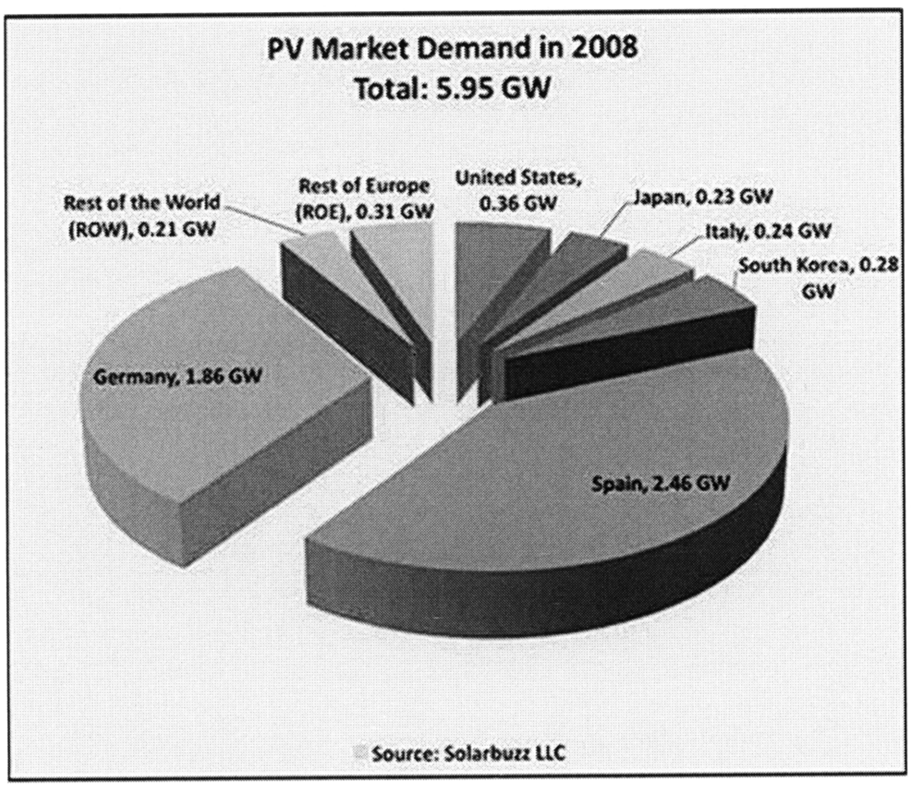

Figure 23: PV market demand by country in 2008 Source: Solarbuzz

A spike in the demand for PV panels in Germany during the last decade caused by the attractive German feed in tariff policy stressed the supply of solar grade silicon which is the most utilized semiconductor material in the manufacturing of PV modules. This shortage caused the price of solar grade silicon to increase from $24 per kg in 2003 to $450 per kg in 2008, which caused the price of PV panels to increase also [39]. High silicon prices caused PV companies and labs to develop new PV technologies that use different materials than silicon. These are called thin film PV; they are cheaper than their silicon counterparts and currently hold 14% of the PV market [40]. Since the shortage in silicon supply began, many silicon refining plants have been under construction, which are expected to bring the price of silicon down and consequently the price of PV when they begin operations. In the global market, the main disadvantage of PV is its high price. PV is a proven technology with hundreds of companies developing the technology around the world. It should also be mentioned that the PV manufacturing process is very sophisticated and high tech; there are many manufacturing processes, materials and designs used by different companies in the development of this technology.

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
United Solar	US	a-Si (3)	7.9	stainless steel	vapor-deposition, roll-to-roll
Kaneka Silicon PV	Japan	a-Si	6.3	glass	chemical vapor deposition
Shenzhen Topray Solar	China	a-Si (2)	7	glass	chemical vapor deposition
Mitsubishi Heavy Industries	Japan	a-Si, µc/a-Si(2)	7.3	glass	plasma chemical vapor deposition
Bangkok Solar	Thailand	a-Si (2)	5.1	glass	chemical vapor deposition
Ersol Thin Film GmbH	Germany	a-Si	6	glass	chemical vapor deposition
Fuji Electric	Japan	a-Si		plastic film	roll-to-roll
CSG Solar AG (Pacific Solar)	Germany	c-Si	7	glass	deposition, laser printing, sputtering
SCHOTT Solar GmbH	Germany	a-Si (2)	5.3	glass	plasma deposition
Sharp	Japan	µcSi/a-Si	8.1	glass	dual layer deposition
PowerFilm Solar (Iowa Thin Films)	US	a-Si	5	flexible polymer	printing, roll-to-roll & monolithic integr.
Energy Photovoltaics (EPV)	US	a-Si (2)	5.5	glass	chemical vapor deposition
Terra Solar	US	a-Si	6	glass	plasma chemical vapor deposition
Sanyo Solar	Japan	a-Si (HIT)		various	plasma chemical vapor deposition
Heliodomi S.A.	Greece	a-Si		glass	chemical vapor deposition
Sinonar	Taiwan	a-Si		glass	chemical vapor deposition
Tianjin Jinneng Solar Cell Co.	China	a-Si		glass	chemical vapor deposition
ICP Solar (Intersolar)	Canada	a-Si	4.5	various	deposition & laser scribing
Flexcell (VHF Technologies SA)	Switzerland	a-Si	5.5	plastic	plasma deposition, low temperature
Free Energy Europe	France	a-Si	5	glass	chemical vapor deposition
API GmbH	Germany	a-Si		glass	chemical vapor deposition
Brilliant 234 GmbH	Germany	µcSi/a-Si	8	glass	chemical vapor deposition
Moser Baer	India	µcSi/a-Si	8	glass	chemical vapor deposition
NexPower Technology	Japan	a-Si (2)		glass	chemical vapor deposition
Solems	France	a-Si		glass	chemical vapor deposition
Gen3 Solar	US	a-Si		glass	chemical vapor deposition
XsunX	US	a-Si		glass	plasma chemical vapor deposition
Solar Cells (Koncar)	Croatia	a-Si	4.9	glass	chemical vapor deposition
Calyxo GmbH	Germany	a-Si		glass	chemical vapor deposition
HelioGrid	Hungary	a-Si		glass	chemical vapor deposition
T-Solar	Spain	µcSi/a-Si	8	glass	chemical vapor deposition
Sunfilm AG	Germany	µcSi/a-Si	8	glass	chemical vapor deposition

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
First Solar	US	CdTe	9.5	glass	high-rate vapor deposition
Antec Solar Energy GmbH	Germany	CdTe	6.9	glass	chemical deposition & sputtering
Solar Fields. LLC	US	CdTe	9.5	glass	atmospheric pressure deposition
Primestar Solar	US	CdTe		glass	
AVA Technologies LLC	US	CdTe		glass	Air-to-Vacuum-to-Air (AVA) belt transport
Canrom	US	CdTe		glass	
Matsushita Battery	Japan	CdTe		glass	printing & sintering or CVD
Golden Photon	US	CdTe			

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
Miasole	US	CIGS	10	stainless steel foil	sputtering & roll-to-roll
Johanna Solar (Aleo Solar)	Germany	CIGS		glass	sputtering & chemical bath deposition
Honda Soltec	Japan	CIS			
Showa Shell Sekiyu	Japan	CIGS			
Wuerth Solar GmbH	Germany	CIS	11.5	glass	multi-source evaporation
DayStar Technologies	US	CIGS	10	flexible metal	sputtering & batch (gen2) or roll-to-roll (gen3)
Global Solar	US	CIGS	10.9	flexible steel foil	deposition & roll-to-roll
Sulfurcell	Germany	CI Sulfide	6.1	glass	deposition
Odersun	Germany	CIS	10	glass	roll-to-roll
Ascent Solar	US	CIGS	9.5	plastic	roll-to-roll & monolithic integration process
Avancis	Germany	CIS	9.4	glass	deposition
HelioVolt	US	CIGS	12	glass or metal	rapid, low temp process w/ monolithic integr.
Nanosolar	US	CIGS	10	flexible metal	printing & rapid thermal processing
Solibro GmbH	Germany	CIGS		glass	
Solarion GmbH	Germany	CIGS		flexible polymer	roll-to-roll process
International Solar Electric (ISET)	US	CIS		glass	non-vacuum approach
Flisom	Switzerland	CIGS		plastic	roll-to-roll & deposition
SoloPower	US	CIGS			electrochemical process
Solyndra	US	CIGS			sputtering
InterPhases Research	US	nCIS		flexible metal	roll-to-roll electroplating process
ITN Energy Systems	US	CIS		various	
Scheuten Solar	Netherlands	CIS		glass	

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
G24 Innovations	Wales	DSC	5	plastic	roll-to-roll
Dyesol	Australia	DSC		glass	roll-to-roll
Konarka	US	organic	target 5%	plastic	roll-to-roll, low-temperature
Innovalight	US	nano			
Stion	US	nano			
Global Photonic	US	organic			
Plextronics	US	organic		plastic	
Octillion	Canada	nano		glass	
SCHOTT Solar	Germany	DSC			
Solaris Nanoscience	US	DSC		plastic	roll-to-roll
AISIN Seiki	Japan	DSC		plastic	

Figure 24: Some companies developing different PV technologies Source: Grama, Sorin May 2007, A Survey of Thin-Film Solar Photovoltaic Industry & Technologies, MIT

4.2 CSP Technologies

CSP technologies are built on a science different from that used by PV technologies. While we saw that PV technologies are compact electronic systems that generate electricity directly, we will now turn our attention to a more mechanical system that generates electricity indirectly. CSP technologies operate focus the suns energy using various mirror configurations, in order to produce high temperature heat. Thermal power generated by these CSP designs is then sent to a conventional generator to produce electricity. This divides CSP power plants into a part that collects solar energy and converts it to heat, and another part that converts the heat into electricity.

The part of the CSP power plant that collects heat and converts it to electricity is a very well developed technology that is used by coal and natural gas power plants. The difference is that fossil fuel power plants create their heat by burning fuel, while CSP power plants create heat by focusing the sun's energy, and both use the same technology to convert heat into electricity. There are 4 main CSP technologies used for electricity generation, which we will discuss in this section.

Parabolic Trough Technology

This technology uses parabolic shaped reflectors to concentrate the sun's energy more than 50 times on an absorber tube, located at the parabola's focal point. The absorber tube contains a working fluid that is heated up by the focused energy to temperatures up to 400 degrees Celsius. The working fluid is then passed to a conventional power bloc which usually contains a heat exchanger and a steam turbine in order to generate electricity.

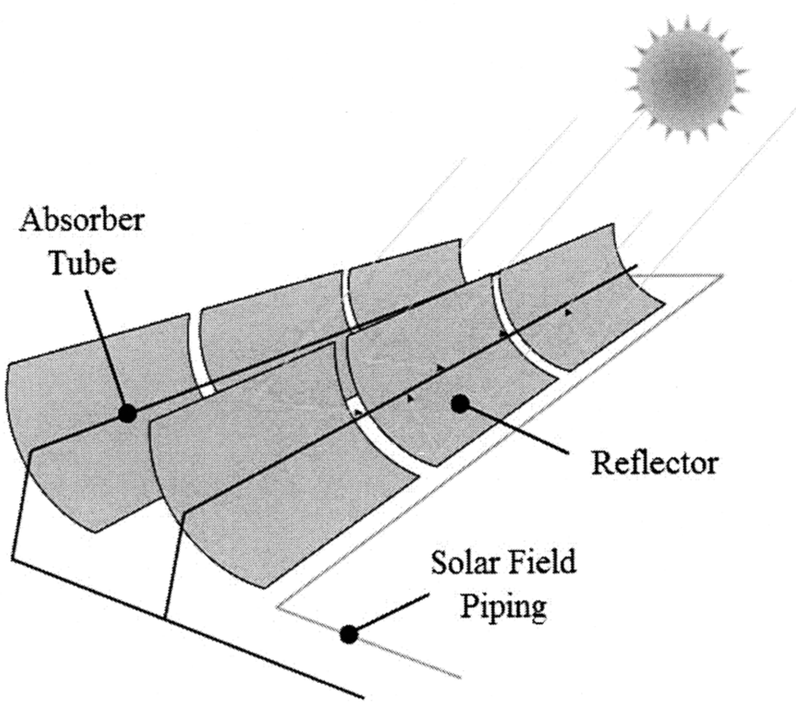

Figure 24: Parabolic trough concept Source: Wikipedia

Parabolic trough designs use mirrors that are manufactured with very high degrees of accuracy in order to form the angles required to focus all the incoming light on the absorber tube. In addition, the overall solar collector must be designed and assembled very accurately in order to ensure that the absorber tube is positioned exactly at the focal point and that all the mirrors are placed at the right angles to create the extremely accurate parabolic shape that is necessary for the technology to work efficiently. If any of the critical components deviate from the required geometry by a few millimeters the efficiency of the system is reduced dramatically.

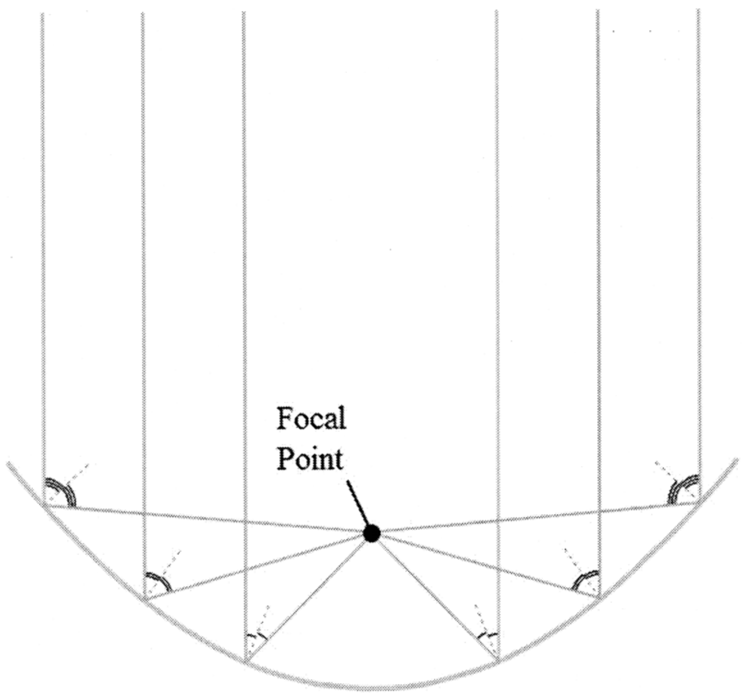

Figure 25: shows how all the components must be aligned carefully to provide the angles required for the light to be focused on the absorber tube   Source: Wikipedia

An extremely large area of parabolic trough collectors is required to generate the heat required by turbines in power plants to produce large amounts of electricity. This collection of parabolic trough collectors is referred to as the solar island or the collector field. A solar island is compromised of many troughs of this design placed in parallel rows. Each troughs extends to over a 100 meters long and is aligned on a north-south axis to enable the use of tracking systems to rotate the troughs and track the sun from east to west. Thus ensuring that the sun is continuously focused on the absorber tubes.

Figure 26: parabolic troughs place in parallel on a solar island in Mojave Desert, California

Source: DOE

Out of all CSP technologies, parabolic trough technology is the most developed and most economic technology currently used for utility scale power plants today. Large scale parabolic trough power plants have been operational in California's Mojave Desert since the 1980's. The Mojave Desert now has nine CSP power plants based on the parabolic trough design with a total capacity of 354 MW [41]. Having a lifetime of almost 30 years, these plants in California are a testament to the low risk and sound development of the technology. Around the world there are 1,270 MW of parabolic trough power plants, with most of those being in Spain and the U.S [42]. Because of it has been in the commercial stage since the 1980's, there are more parabolic trough power plants being constructed than any other solar technology today. Electricity costs from the

Andasol 1 power plant in Spain using this technology are 16 euro cents per kWh. Electricity costs decrease in regions with higher amounts of solar irradiance.

Fresnel Technology

Recently, a new design modification to parabolic trough technology has been developed that reduces the cost and complexity of the system. This is referred to as Fresnel design, which approximates the parabolic trough design by using segmented flat plate mirrors as seen in figure 27.

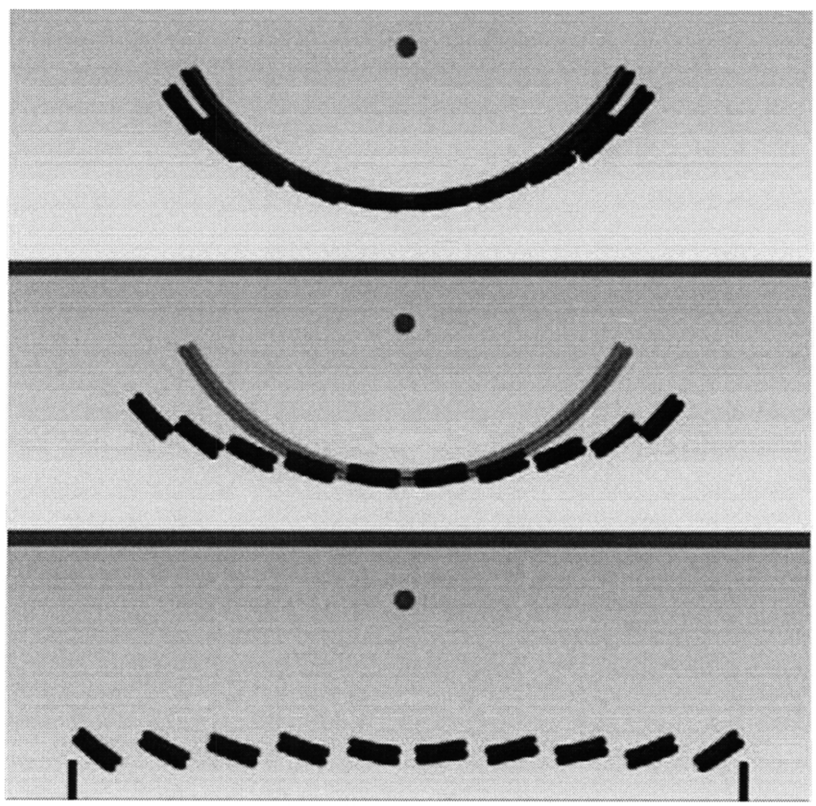

Figure 27: Approximation and simplification of the parabolic trough design by the Fresnel design. Source: Nokraschy Engineering GmbH

In the Fresnel design light is reflected onto the absorber tube from a series of long, narrow mirrors below it. A small mirror can be attached on top of the absorber tube for further focusing.

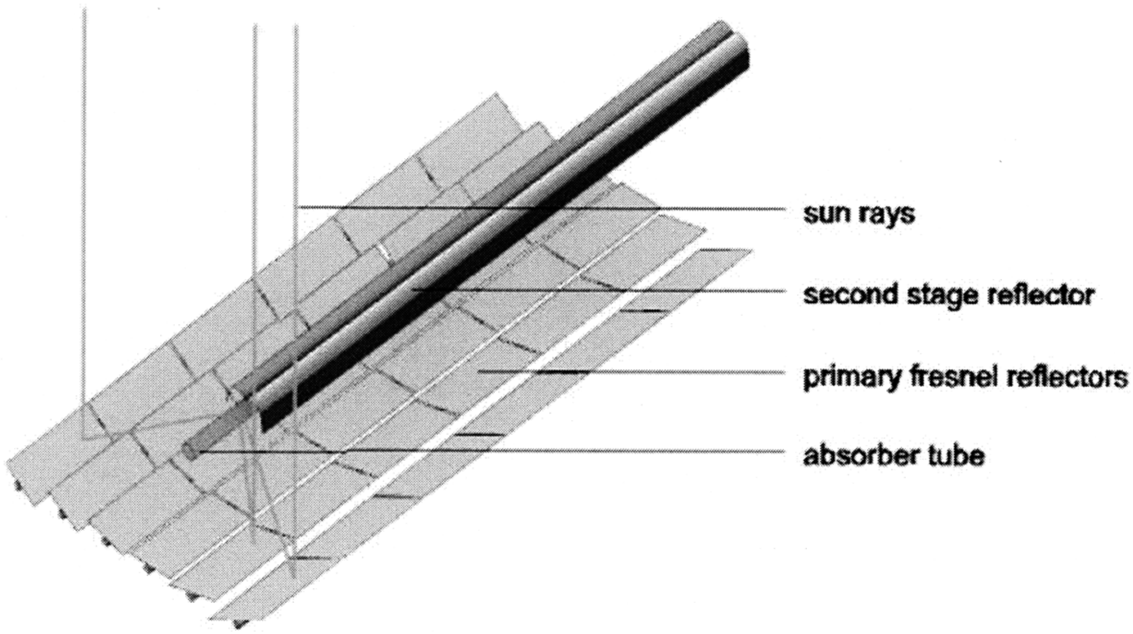

Figure 28: Design of the Fresnel collector Source: Solarmundo

In addition to making simplifications to the mirrors the Fresnel design also uses pressurized water as the Heat Transfer Fluid (HTF) in the absorber tube and thus reduces the need for an expensive HTF. Since the Fresnel design uses water as the HTF, there is no need for a heat exchanger in the power bloc and thus costs are reduced further as the HTF generates steam directly after which, it is drive the steam turbine. Because of these approximations, the Fresnel design is less efficient than the parabolic trough design. This is compensated by the cost reductions achieved by these simplifications which result in a lower cost per kWh of electricity generated. The Fresnel design thus leverages the developed track record of the parabolic trough design in addition to introducing technical simplifications that result in a lower system cost.

Given its recent development, Fresnel technology has been applied rapidly in the last seven years since its first designs. It has been tested successful on small prototype scales in Belgium and Germany, in addition to large scale demonstration projects and utility projects. The latter include the the 5 MW Kimberlina Solar Thermal Energy Plant in Bakersfield, California. In addition to the 360 KW Lidell Power Station in New South Wales, Australia which was developed in hybrid with an existing power plant. Moreover, there are 600 MW in capacity of projects that have been announced for construction in Florida and California alone.

The two companies that lead the construction of solar power plants based on the Fresnel design, are Ausra, an Australian company and the Solar Power Group GmbH, located in Germany, which used to be the Solarmundo research and development project that was responsible for the successful prototype in Belgium.

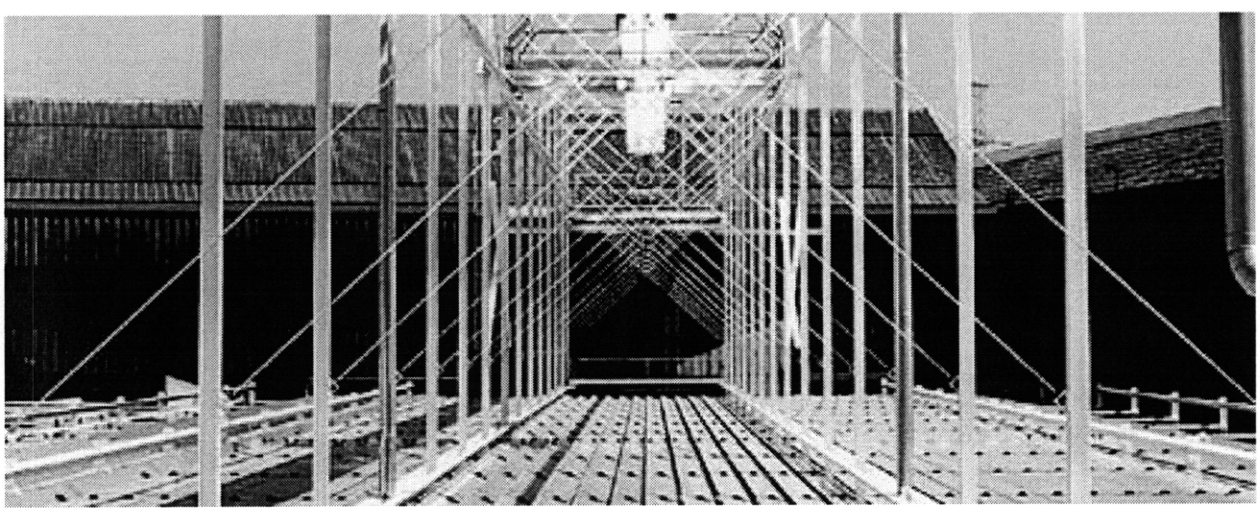

Figure 29: The Fresnel collector developed by Solarmundo during their project in Belgium

Source: Solarmundo

Other CSP technologies

There are three other promising CSP technologies that are currently under development and are more expensive than parabolic trough and Fresnel technologies. Since they are not as mature nor economic as other CSP technologies we will only briefly mention them.

Power Tower

Power tower power plants use an array of flat, moveable mirrors called heliostats to focus the sun's rays upon a central collector tower.

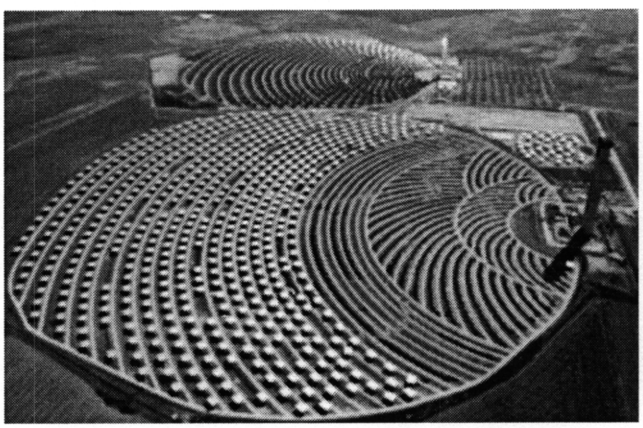
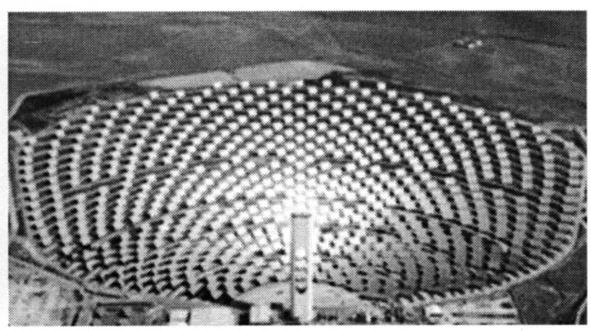

Figure 30: The PS10 Power Tower power plant in Spain Source: Abengoa

The advantage of this design over the parabolic trough design is that it can achieve higher temperatures. This is an advantage because thermal energy at higher temperatures can be converted to electricity more efficiently and can be stored for later use at a cheaper cost. However, Power tower technologies are more expensive than parabolic trough because the technology has not achieved modularity yet. In other words, the design is dependent on one very large central tower that has a very large capital cost. If modular power towers can be developed in a feasible way, they can become more economic than parabolic trough technology. Currently all the Power Tower plants constructed use a central tower and thus the technology is still under development.

Stirling Dish

A dish Stirling system uses a large, reflective, dish similar in shape to a satellite television dish. It focuses the incoming sunlight striking the dish onto to a single point above the dish, where a Stirling engine is in place to transform the heat into electricity. These systems also have the advantage of producing higher temperature heat and thus are more efficient. However they are more expensive than parabolic trough and Fresnel technologies when it comes to large scale power plants.

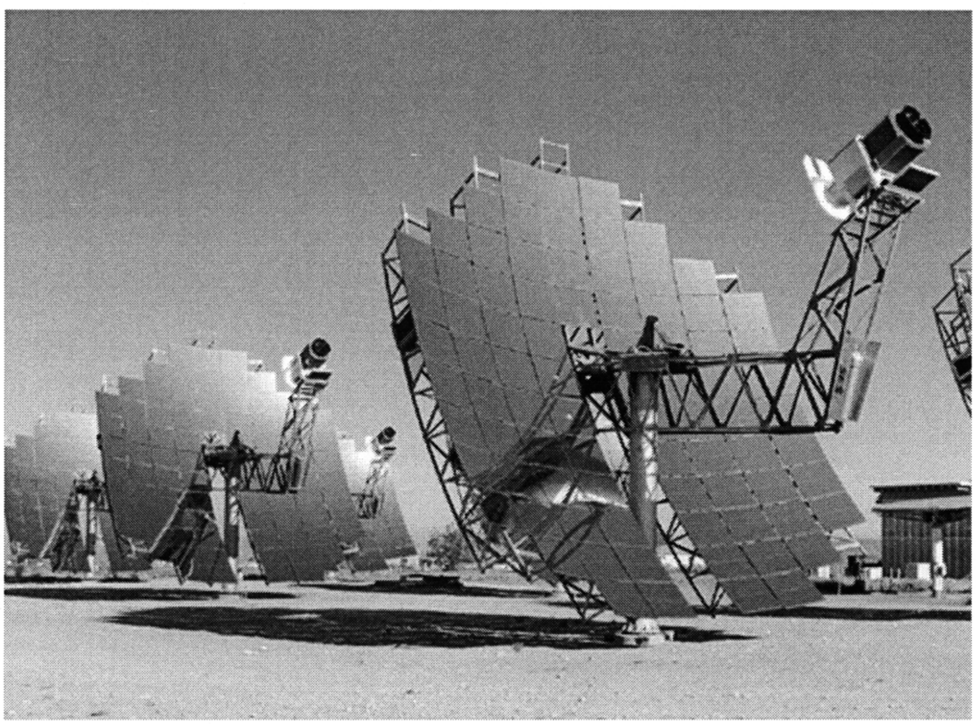

Figure 31: A solar stirling dish Source: SES Stirling Energy Systems

Chapter 5: Which Solar Technology Can Egypt Develop an Industry Around?

5.1 Assessment Framework

The choice of which technology Egypt should develop an industry around could change depending on the factors used in the technology assessment. Consequently we will establish clearly these factors and the assessment framework we will use before we start investigating the various technologies.

Cost per kWh of Electricity Generated from Solar Energy System

The first factor we will use in our assessment is the cost per kWh of electricity generated from the technology. This factor is important because a lower cost of electricity will increase utilization of solar energy. This increased utilization will stimulate and increase the share of local manufacturing of the technology in order to decrease the cost of a highly demanded product. This in turn will also stimulate local research and development in the technology in order to develop better products.

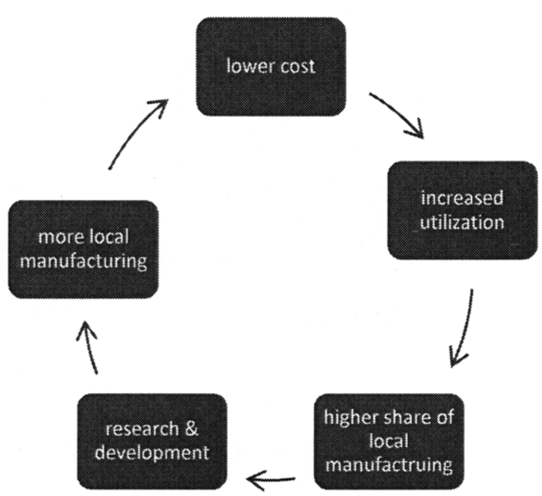

Figure 32: Low cost effect on industry

In addition the cost per kWh of electricity generated is an important factor for the obvious reason that makes one product better than the other if it provides the same service at a lower cost.

Technical Feasibility to Build and Maintain

The second factor we will use in our assessment is the technical feasibility of building and maintain large scale solar systems from this technology in Egypt. Different technologies would be more or less feasible to build and maintain depending on the set of skills and capabilities required to perform those tasks, and whether these skills and capabilities are available in Egypt. Therefore this factor is important because it can determine which technology can be deployed faster in Egypt and thus increase the pace and scale at which the industry is being built

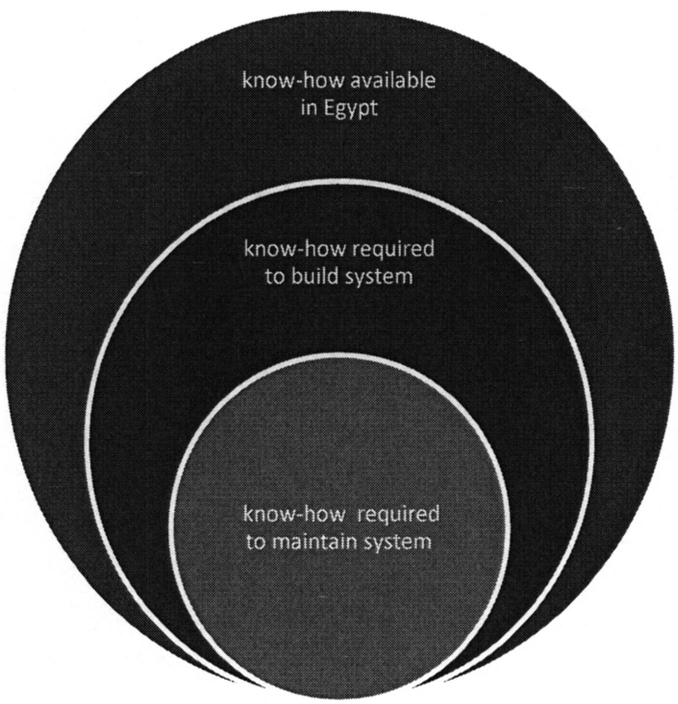

Figure 33: example of a technology that is technically feasible to build and maintain a system of in Egypt

Local Manufacturing

The third and last factor we will use in our assessment is which technology can be manufactured locally. While the second factor dealt with the technical feasibility of building and maintaining a large scale system using this technology in Egypt, the third factor focuses on whether the components of the technology can be manufactured locally. Local manufacturing is important because when it is technically and economically feasible it will reduce the cost of the technology, develop better know how in this field, encourage research and development and create more jobs. Consequently local manufacturing plays an integral role in the development of a complete industry.

Since the power tower and the stirling dish technologies have not become mature technologies yet and have yet to achieve significant cost reductions by the companies and institutions developing these technologies, we will exclude them from our detailed analysis of CSP technologies. It is better to wait until, these technologies have fully matured and achieved higher cost reductions from the investments and experimentation of European countries and the US, before these two technologies are used on an industry wide scale in Egypt. Thus, we will focus our assessment on PV, Parabolic Trough and Fresnel solar technologies.

5.2 PV Technology Assessment

Cost

As we have seen before, PV is currently one of the most expensive solar technologies. One of the reasons behind the high prices of PV technology is because the current modules have an average efficiency of 10%, and although they have a low efficiency they are also expensive to manufacture. The technology is realizing incremental increases in efficiency every year as a result of the millions of dollars poured into research and development. Currently the cheapest PV systems used in Egypt generate electricity at a price of $0.25 per kWh.

PV solar panels have been used in Egypt for remote off grid applications such as street lights, telecommunication towers and remote ambulance stations. All of these applications require a relatively small amount of power and are not connected to the grid, which made the use of PV panels economically feasible for those applications.

This makes other CSP technologies much more economical when it comes to electricity generation on a large scale. We have seen that CSP technologies in even less sunny countries than Egypt such as Spain can generate electricity at a much lower price of 0.16 euros per kWh for Spain's Andasol 1 plant for example. In addition, PV systems require batteries to store electricity, while CSP storage systems store heat that is later used to generate electricity on demand by the turbine. Battery systems are much more expensive than the thermal storage systems used by CSP technologies, which further adds to the price gap between PV and CSP.

Technical Feasibility

There are currently seven companies that sell PV technology in Egypt most of their sales go to remote applications as mentioned before. PV technology has performed very well in their niche of small scale applications in Egypt. However, for large scale applications the systems did not perform as well. The first reason for this is the high temperatures associated with the Egyptian desert, where temperatures could go beyond 40 degrees Celsius. PV panels decrease in efficiency by about 4% for every 10 degrees Celsius increase above ambient temperature. On a large scale system using a technology that is already low in efficiency, this further loss in efficiency strongly affects performance.

The second problem faced by large PV systems in Egypt is maintenance. Since the Egyptian companies do not manufacture PV modules and instead import them from Europe and Japan, they do not have the fundamental understanding of the technology that would allow them to troubleshoot and resolve any scenarios that need repair. While perhaps suppliers could replace malfunctioning modules in small applications, on a large scale system the lack of professional maintenance is obviously a big problem.

Local manufacturing

The seven companies that sell PV technology in Egypt import PV modules and assemble them into systems. These companies' technical contribution is installing the PV panels on the site and assembling the system by connecting components such as batteries, wires and inverters to the PV panels. Consequently, there is almost no local manufacturing involved with regards to PV technology in Egypt. The only share of local manufacturing is some of the simple components required to make up the system such as electrical cables and a protective aluminum frame for the PV modules. This puts the share of local manufacturing for PV modules at 0%.

In the figure below, we can see the supply chain involved in the development of PV technology. The first step is the purification of silicon to a level of at least 99.9999% in order to make solar grade silicon. The last step is the development of solar modules that the Egyptian companies import and assemble into PV panels and systems.

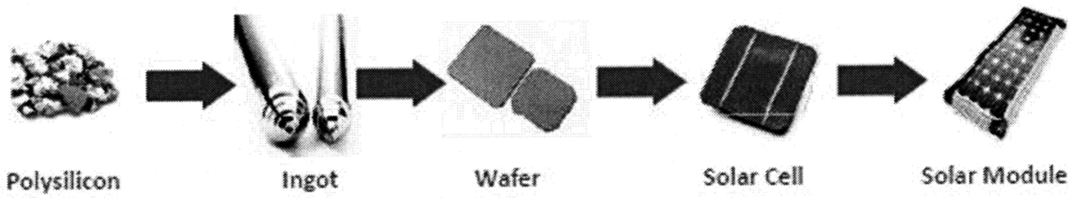

Figure 34: various stages involved in the development of PV solar modules

Source: Solarbuzz

Each of these processes use very advanced equipment and machinery in addition to a very highly skilled and experienced set of technicians and engineers. Neither the know-how of developing any of those processes, nor the necessary infrastructure is available in Egypt. Consequently, it will be very hard for Egypt to locally manufacture solar energy systems based on the PV technology in the near future.

Summary

As a result of its high cost compared to other solar energy technologies, decreased efficiency as a result of the high temperatures of Egypt, and the limited maintenance services available in the country, PV is not the best technology to utilize on a nationwide scale in Egypt. In addition, the very high learning curve required and the intensive capital costs that are required to manufacture PV technology locally do not make it a good choice of technology to build a solar energy industry around in Egypt in the near future. In the next section we will explore CSP technologies, after which we will be able to see if they would be a better choice than PV technology.

Factor	Result
Cost per kWh of electricity generated	More than 25cents per kWh
Technical feasibility of deploying and maintaining on a large scale	Maintenance problems and less module efficiency as a result of the high temperatures of Egypt.
Ability to manufacture locally	- 0% of the PV module can be manufactured locally. - Local manufacturing requires very high human and capital investments - Will also require a long term learning curve to produce effective results.

Figure 35: Summary of PV assessment

5.3 Parabolic Trough Technology Assessment

Cost

The use of parabolic trough technology in large scale utility power plants since the 1980's allowed the technology today to generate some of the lowest solar electricity prices. We know that the Andasol 1 parabolic trough power plant in Spain generates electricity at a cost of 0.16 Euros per kWh. Because Egypt receives an amount of solar irradiance that is almost double what Spain and other southern European countries receive, the cost of electricity from parabolic trough power plants in Egypt is much lower.

To calculate how much less the cost of electricity from parabolic trough technology would be in Egypt, let us consider a 50 MW solar power plant that could be built with parabolic trough technology in Hurghada, Egypt. Hurghada is located on the Red Sea, and has a very large solar resource, it receives 2782 kWh per square meter of direct normal irradiance (DNI) from the sun every year. Current parabolic trough collector's efficiency allows it to capture 50.1% of the sun's energy [43]. The Figure below gives a breakdown of the costs of electricity that such power plant would generate in Hurghada.

System Layout	
Power	50 MW
Power Block Efficiency	33%
Collector Area	261,600 meters squared
Investment	
Power Block	33,993,000 euros
Specific Field	220 euros per meter squared
Solar Field	57,552,000 euros
Total Investment	91,545,000 euros
Cost	
Interest Rate	6.70%
Economic lifetime	28 Years
Capital Cost	7,325,000 euros
Insurance Cost	654,000 euros
Operation & Maintenance Cost	2,184,000 euros
Total Annual Cost	10,163,000 euros
Yield per meter squared	
Solar Resource	1,752 kWh per year
Usable Thermal Energy	1,393 kWh per year
Lower Dumping	38 kWh per year
Upper Dumping	27 kWh per year
Electricity yield	460 kWh per year
Total Yield	
Solar Resource	458 GWh per year
Usable Thermal Energy	364 GWh per year
Electricity yield	120 GWh per year
Electricity Cost	8.45 euro cents per kWh

Figure 36: Electricity costs break down if a parabolic trough power plant is built in Hurghada

Source: German Aerospace Center (DLR) Institute of Technical Thermodynamics-Solar Research. Solarmudo

The 0.0845 Euros per kWh resulting electricity costs from a parabolic trough solar power plant in Hurghada Egypt, is almost half the cost of its counterpart in Spain. This is also more than half the cost of solar electricity generated from PV technology in Egypt.

Technical Feasibility

There is currently a 140 MW Integrated Solar Combined Cycle (ISCC) power plant being constructed in Kuraymat, Egypt. This is the first solar power plant in Egypt and the Middle East. The owner of the project is the Egyptian government which selected the Kuraymat location in order to spare land in Hurghada for wind energy projects, since wind speeds there are the highest in the MENA region.

Construction of the power plant will be complete in 2010 [44]. The solar component of the power plant is has a share of 20 MW, which is based on a solar island of parabolic trough design. An Egyptian construction company called Orascom Construction Industries, is leading the project in partnership with a German company called Flagsol, that is a leader in the design, development and operation of parabolic trough power plants.

All the necessary knowhow required to build the plant has been transferred to the local engineers as a result of the partnership with Flagsol. This includes the know-how of building and assembling the structure with the very high precision required to give the collector the accurate parabolic structure required, which is most challenging part of constructing a large scale parabolic trough system. Consequently, Egypt can now build large scale solar power plants based on the parabolic trough technology.

With regards to operation and maintenance of the plant, the Egyptian government has signed a contract with the German technology provider to provide O&M services for the plant for two years while training a group of Egyptian engineers so that they can accomplish all the necessary tasks required to run the power plant independently.

Flagsol has built many of the worlds parabolic trough power plants including some of the ones in California's Mojave desert. Consequently, the same training required to achieve long term operation of the Spanish and American power plants has been transferred to Egypt.

The high temperatures of the Egyptian deserts that would cause an efficiency reduction for PV technologies does not negatively affect parabolic trough technology in the same way since the working fluid in the solar collector can withstand temperatures up to 400 degrees Celsius. Thus the technology was built for desert like environments.

As we have mentioned before, almost all of Egypt's power plants have been built using a steam turbine or a combined cycle. This means that it is technically feasible to build a parabolic trough solar island next to the existing power plant and integrate them, allowing them to use solar energy during the day and fossil fuels at night (thermal storage could allow the use of solar energy at night also). This leverages existing infrastructure in the country in a way that PV technology cannot do. All of this makes it technically feasible for Egyptian personnel to build, operate and maintain large scale parabolic trough power plants in addition to integrating new solar islands with existing fossil fuel power plants all over the country.

Local Manufacturing

As previously mentioned, we will focus our analysis on the solar island since the power bloc required by CSP technology is the same one used in most of the Egyptian power plants. Therefore new parabolic trough solar islands can be integrated with the existing power plant infrastructure in Egypt.

The steel used to build the support structure for the parabolic trough collector must be fabricated with extremely high precision to give the collector the accurate parabolic geometry required. The German technology provider in the Kuraymat project advised the Egyptian National Steel Fabrication company (NSF) on the purchase of the necessary machinery and development of the required processes to fabricate steel with such high accuracies. In addition to the steel supplied by NSF, the concrete used to develop the ground foundation for the collectors (which must also be very accurate) was locally produced. The combination of the ground foundation and the steel structural support for the collector is referred to as civil works. The cost of the civil works represent a 50% financial value of the solar island, since every other component involved in the parabolic trough solar island is imported from abroad, we can say that 50% of the project is locally manufactured. However, if we exclude civil works then 0% of the technology is currently locally manufactured.

To increase the locally manufactured share of the technology, attempts have to be made to develop locally the three most critical and most used components. These are the reflective material, the absorber tube and the working fluid. Almost all large scale parabolic trough power plants use the same product for each of those components.

Reflective Material

The reflective material used in almost all parabolic trough power plants is thick mirrored glass supplied by Flabeg, a German company that is a sister company of Flagsol. Manufacturing these mirrors requires a very accurate production process that gives the mirrors the exact curvature required, this process is referred to as hot bending. Currently there are a few factories in Egypt that use hot bending to manufacture glass for automotive applications. However these processes do not compare to the scale of efficiency required in mirrored glass and are instead basic hot bending rather than the extremely sophisticated type required.

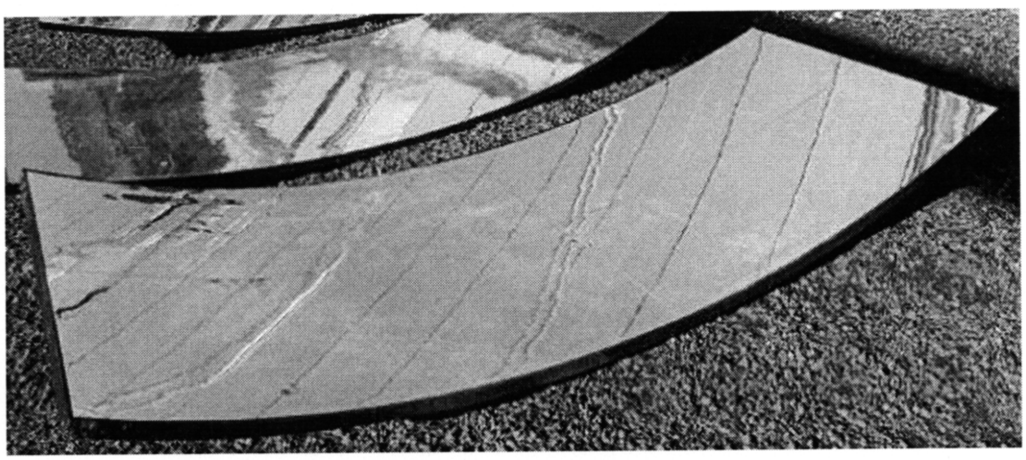

Figure 37: Curved mirrors obtained through hot bending process Source: Flabeg

Consequently, in order to develop reflective material locally, Egypt must get Flabeg's technical support in order to set up a manufacturing facility in Egypt and train its engineers to use these manufacturing facilities. This would only be realistic if Flabeg sees benefits for itself to enter into this agreement, such as lower factory operating cost in Egypt as a result of cheap labor, energy and raw materials; financial incentives provided by the government and a gateway to the

Egyptian and Middle Eastern market which have enormous potential for parabolic trough power plants.

Another alternative is to use a different material than glass, the reflective material is not restricted to glass it just has to have good reflective qualities. Thick glass is the most commonly used material because it is very robust and can withstand harsh climate conditions. Egypt therefore could also investigate engineering other materials such as reflective aluminum with protective layers or organic materials, both which don't require a hot bending process.

Absorber tube

The absorber tube used in almost all large parabolic trough power plants around the world is supplied by Schott, another German company.

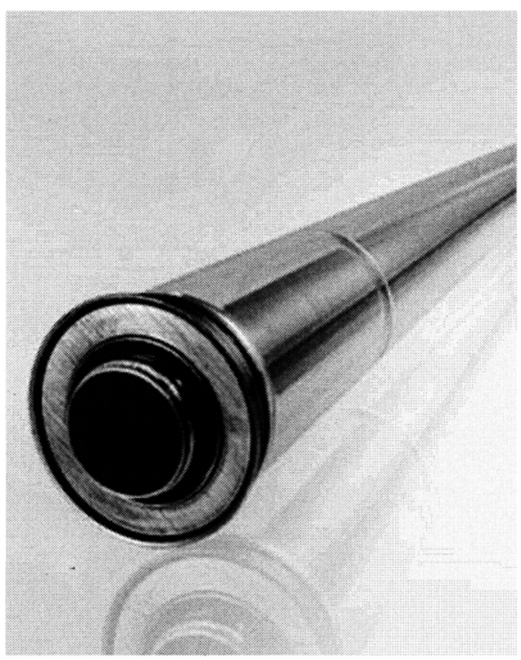

Figure 38: Schott absorber tube Source: Schott Solar

Shott's modular 4 meter absorber tubes (also referred to as a receiver) are used along the focal point of collectors that are hundreds of meters in length. These tubes have been designed with high precision to achieve high efficiencies. Schott's absorber tubes are vacuum-sealed and contain a glass envelope surrounding them. The glass envelope is made of robust borosilicate glass and has an anti reflection coating to increase absorption of the sun's radiation by up to 96%. Like the glass envelope the absorber tube also has a selective coating that allows high absorption of 95% and little emitting of the sun's radiation back to the atmosphere (below 14%). All of this can be achieved at very high operating temperatures of up to 400 degrees Celsius [45].

Similar to the case with the reflective material, to locally develop the absorber tube, a manufacturing facility could be developed in partnership with Schott or one of its competitors in order to develop high standard absorber tubes. On the other hand, since the absorber is fundamentally a steel pipe with a glass envelope around it and some selective coatings to increase efficiency, the development of this component could be engineered in Egypt using less efficient but cheaper locally available materials.

Working Fluid

Finally, Therminol VP-1 is the heat transfer fluid (HTF) used in most parabolic trough power plants and it is developed by Solutia, an American company. Therminol VP-1 is a synthetic HTF with excellent heat transfer properties and can withstand the high operating temperatures of parabolic troughs, up to 400 degrees Celsius. It is a mixture of 73.5% diphenyl oxide (DPO) and 26.5% biphenyl [46]. Again, with some research, experiments and engineering practice, an alternative to Therminol VP-1 designed to meet similar characteristics of the fluid given in the figure below can be engineered in Egypt.

Appearance	Clear, water white liquid
Composition	Biphenyl/diphenyl oxide (DPO) eutectic mixture
Crystallizing Point	12 °C (54 °F)
Moisture Content	300 ppm
Flash Point (ASTM D-92)	124 °C (255 °F)
Fire Point (ASTM D-92)	127 °C (260 °F)
Autoignition Temperature (ASTM D-2155)	621 °C (1150 °F)
Kinematic Viscosity, at 40 °C	2.48 cSt
Kinematic Viscosity, at 100 °C	0.99 cSt
Density at 25 °C	1060 kg/m3 (8.85 lb/gal)
Specific Gravity (60 °F/60 °F)	1.069
Coefficient of Thermal Expansion at 200 °C	0.000979/°C (0.000544/°F)
Volume Contraction Upon Freezing	6.27%
Volume Expansion Upon Melting	6.69%
Surface Tension in Air at 25 °C	36.6 dyn/cm
Specific Resistivity at 20 °C	6.4 x 10^11 ohm-cm
Average Molecular Weight	166
Heat of Fusion	97.3 kJ/kg (41.8 Btu/lb)
Minimum Vapor Temperatures for	
Fully Developed Turbulent Flow (Re = 10000)	
10 ft/sec, 1-in tube	208 °C (406 °F)
20 ft/sec, 1-in tube	181 °C (358 °F)
Transition Region Flow (Re=2000)	
10 ft/sec, 1-in tube	151 °C (304 °F)
20 ft/sec, 1-in tube	131 °C (268 °F)
Normal Boiling Point	257 °C (495 °F)
Heat of Vaporization at Max. Use Temp 400°C	206 kJ/kg (88.7 Btu/lb)
Optimum Use Range, Liquid Vapor	12-400 °C (54-750 °F) 260-400 °C (495-750 °F)
Maximum Film Temperature	425 °C (800 °F)
Pseudocritical Temperature	499 °C (930 °F)
Pseudocritical Pressure	33.1 bar (480 psia)
Pseudocritical Density	327 kg/m3 (20.4 lb/ft3)

Figure 39: Therminol VP-1 properties Source: Solutia

Summary

Parabolic trough technology is very well suited for large scale development in Egypt. As a result of a power plant of this technology currently being constructed in the country in partnership with a leading parabolic trough technology provider, the know-how required to build, operate and maintain this technology for utility scale systems is available in Egypt. Electricity from this technology is generated at costs less than PV and the technology can be integrated with existing fossil fuel power plants. Furthermore a high percentage of local manufacturing share can be achieved if local research and development projects are undertaken to engineer some of the modular components at a lower cost, by using less efficient locally available materials.

	Rating
Cost per kWh of electricity generated	-0.084 Euros per kWh -almost half the price of electricity from the same technology located in Spain - more than half the price of electricity from PV in Egypt
Technical feasibility to construct and maintain	Know-how required to make, the construction and maintenance process, technically feasible has been transferred to Egypt as a result of joint project with Flagsol (one of the companies leading the deployment of this technology around the world)
Local manufacturing	- Currently at 50% - 0% if you exclude civil works - Absorber, reflector and HTF should be developed locally to increase local manufacturing share - This can be achieved by: -joint ventures - undertaking research projects to engineer less efficient but cheaper components from locally available materials

Figure 40: Summary of Parabolic trough assessment

5.4 Fresnel Technology Assessment

The simplifications made to the parabolic trough design by the newer Fresnel design, leadss to lower collector efficiency in harnessing the solar flux. Fresnel collectors can harness 34.5% of the sun's energy, compared to the 50.1% efficiency of the parabolic trough collector [47]. The figure below compares the optical efficiency of a Fresnel collector and a parabolic trough collector receiving DNI values of Hurghada, Egypt.

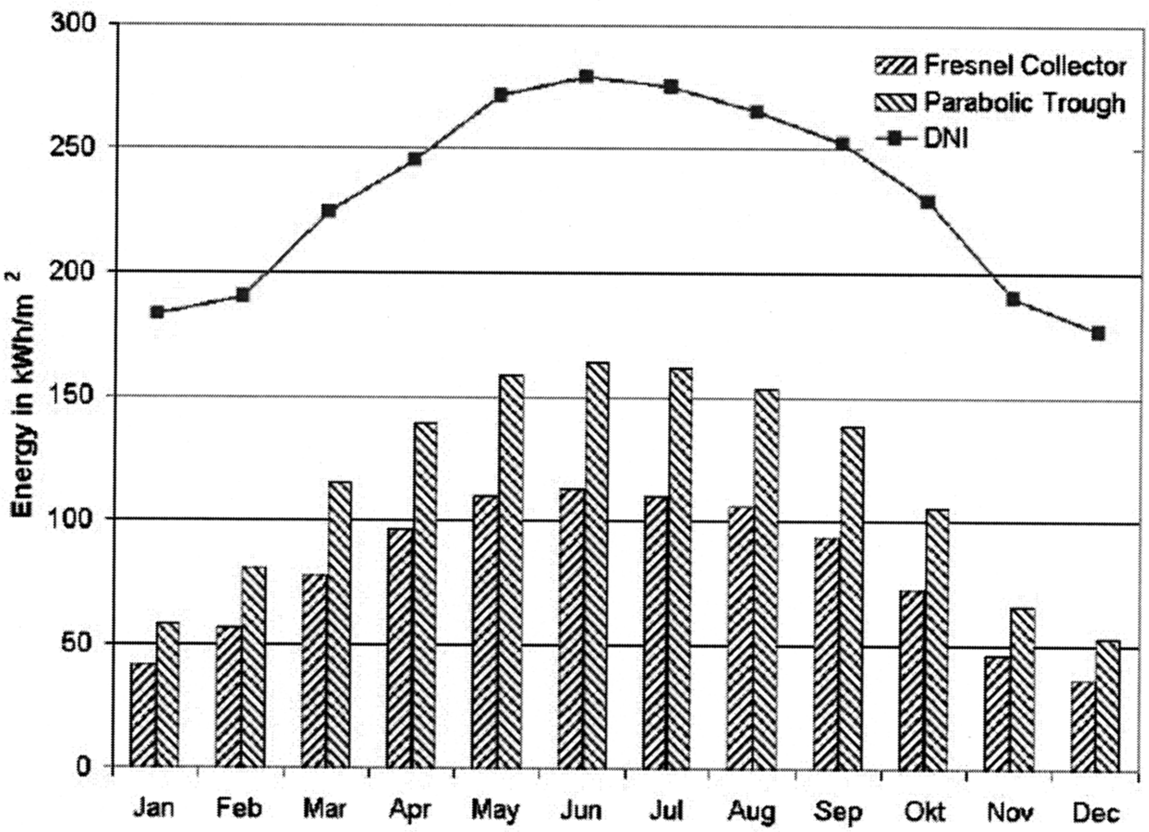

Figure 41: Fresnel and parabolic trough collector optical efficiency, Hurghada DNI conditions
Source: Haberle et Al

Since the Fresnel collector has a lower efficiency it would need a larger area of collectors to provide the same thermal output provided by parabolic trough collectors. Therefore for a 50MW power plant using Fresnel technology 336,700 meters squared of Fresnel collectors would be required. As we have seen before, a power plant using parabolic trough technology would require 261,600 meters squared of collector area to provide an electrical output of 50 MW.

However the simplifications made by the Fresnel design allow it to use less expensive materials that reduce the capital cost of the whole power plant. A break-down of the costs of a 50 MW solar power plant based on Fresnel technology and receiving solar DNI conditions of Hurghada, Egypt is given in figure 42.

Fresnel Technology

System Layout	
Power	50 MW
Power Block Efficiency	33%
Collector Area	336,700 meters squared
Investment	
Power Block	34,832,000 euros
Specific Field	117 euros per meter squared
Solar Field	39,401,000 euros
Total Investment	74,233,000 euros
Cost	
Interest Rate	6.70%
Economic lifetime	28 Years
Capital Cost	5,940,000 euros
Insurance Cost	470,000 euros
Operation & Maintenance Cost	1,570,000 euros
Total Annual Cost	7,980,000 euros
Yield per meter squared	
Solar Resource	1,171 kWh per year
Usable Thermal Energy	958 kWh per year
Lower Dumping	41 kWh per year
Upper Dumping	44 kWh per year
Electricity yield	316 kWh per year
Total Yield	
Solar Resource	394 GWh per year
Usable Thermal Energy	323 GWh per year
Electricity yield	106 GWh per year
Electricity Cost	0.0750 euros per kWh

Figure 42: Source: Haberle et Al

Consequently, the lower efficiency of the Fresnel collector is compensated by the lower cost of materials used, resulting in a lower net cost of electricity produced than that obtained from parabolic trough technology. The simplifications made by the Fresnel technology allow it to generate electricity at 0.0750 euros per kWh, a cost that is 11% lower than electricity from parabolic trough technology and almost 70% lower than electricity from PV technology.

Technical Feasibility

Since the Fresnel technology is a simplification of the parabolic trough technology, both technologies require similar know how capabilities to build power plants of this type. Thus a large component of the know how required to build solar power plants based on the Fresnel technology has been transferred to Egypt as a result of the parabolic trough solar power plant whose construction in Kuraymat is almost complete.

In addition, some of the more simple components used by the Fresnel technology reduces the required technical capabilities, compared to what would be needed in parabolic trough technology include. These simplifications include: inexpensive planar mirrors; simple tracking system; fixed absorber tube with no need for flexible high pressure joints; no vacuum technology and no metal glass sealing; one absorber tube with no need for thermal expansion bows; and no heat exchanger is necessary due to direct steam generation. Furthermore, the development of project managers that can lead the construction of large scale CSP power plants; and the availability of the machinery and skill-set required to fabricate high precision steel structure; in addition to the understanding of the power plant layout and design, are all some of the required

Fresnel technology know-how that is currently available in Egypt as a result of the construction of the Kuraymat parabolic trough solar power plant.

Consequently, all Egypt needs is to build a small scale project in collaboration with one of the leading Fresnel technology providers such as Ausra or Solarmundo to rapidly develop the techniques required for assembly of Fresnel collectors. The country can then leverage its experience in building the Kuraymat parabolic trough solar power plant in building large scale power plants based on the Fresnel design.

Local Manufacturing

The Fresnel design uses simpler components than the parabolic trough design, many of which are already being manufactured in Egypt. For instance, instead of using curved mirrors the Fresnel design can use the same flat plate mirrors that are manufactured locally in Egypt. In addition, there is no need for engineering a heat transfer fluid like Therminol VP-1 since the Fresnel design uses water as the HTF in order to generate steam directly. These simplifications allow the local manufacturing share of the technology to be up to 75%. Consequently most of the materials required to build solar power plants based on the Fresnel technology are readily available in Egypt and so the country can scale up its development of large scale solar power plants very rapidly. In order to increase its local manufacturing share even further, the absorber tubes and the tacking system would have to be developed locally.

Summary

Fresnel technology can generate electricity in Egypt at costs of 0.075 Euros per kWh which makes it the least expensive out of all solar technologies. The simplifications made to the technology in addition to Egypt's current experience in constructing a CSP power plant make Fresnel technology a very suitable solar technology for Egypt. A small scale project of this type in collaboration with one of the leading providers of the technology will allow Egyptian engineers to develop the erection know how of the technology. This will pave the way for large scale deployment of the technology around the country. Finally as result of the simpler components used by the system, up to 75% of the system components are currently manufactured in Egypt and being used for other applications. Local manufacturing share also has the potential to increase with time.

	Rating
Cost per kWh of electricity generated	➢ 0.075 Euros per kWh ➢ 11% lower than Parabolic trough technology ➢ 70% lower than Fresnel technology
Technical feasibility to construct and maintain	➢ Know-how developed from constructing Kuraymat CSP power plant can be leveraged ➢ Simpler design and components make it feasible ➢ Large scale development can be easily managed after small scale project with a leading provider of Fresnel technology
Local manufacturing	➢ Up to 75%, highest share of all solar technologies ➢ Has the potential to increase

Figure 43: Summary of Fresnel Assessment

5.5 Conclusion

Our assessment has shown that PV technology is the least favorable choice of technology to build a solar energy industry around in Egypt. When it comes to large scale deployment CSP technologies can be 70% less expensive than PV technologies. CSP can also provide 24 hour on demand electricity by means of thermal storage which is not economic for PV technologies because of the extremely higher cost of batteries required. The low local manufacturing share of PV technology and the very high capital, infrastructure and training costs required to increase the local manufacturing share make it less attractive than CSP technologies, which have much higher local manufacturing shares and can further increase these shares with less time and investments than what is required for PV. Furthermore, the very high temperatures of the Egyptian desert strongly reduce performance of PV systems and thus CSP technologies are a better fit because they are designed to operate at very high temperatures. PV does an excellent job at serving a niche market for remote small scale power loads in Egypt; however it does not have the characteristics of CSP that would allow it to become the backbone of a large solar energy industry in Egypt.

Since Fresnel technology has the least cost of electricity generation, the highest share of local manufacturing and is feasible to build and maintain in Egypt on a large scale, it is the best choice of technology to build an industry around in Egypt. After a small scale project in partnership with a leading designer of solar islands based on Fresnel technology, the technology would be ready to be integrated with power plants all over the country. In addition to its lower cost, Fresnel technology is better positioned over parabolic trough technology because most of the critical components are readily available in Egypt. The critical components for the parabolic trough design require additional research and investments to develop in Egypt.

	PV	Parabolic Trough	Fresnel
Cost in Euros per kWh of electricity generated	➢ 0.25	➢ 0.0845	➢ 0.075
Technical feasibility to construct and maintain	➢ Maintenance problems ➢ High temperatures of Egypt significantly reduce efficiency	➢ Has been successfully done before in Egypt	➢ Know-how developed from constructing Kuraymat CSP power plant can be leveraged ➢ Simpler design and components make it feasible ➢ Large scale development can be easily managed after small scale project in partnership with a leading provider of Fresnel technology
Percent of technology that can be locally manufactured	➢ 0% of the PV module is manufactured locally ➢ Local manufacturing requires very high human and capital investments ➢ Will also require a long term learning curve to produce effective results	➢ Currently up to 50% ➢ 0% excluding civil works ➢ Research and engineering is required to increase share	➢ Currently up to 75% ➢ 50% excluding civil works ➢ Further increases are possible

Figure 44: Summary of Solar technology assessment

Chapter 6: Conclusions & Recommendations

The rapidly increasing Egyptian population and the fast growth of the country's energy consumption present very serious challenges to the Egyptian government. These challenges will results in a strong stress and eventual depletion in some cases of the country's current energy resources. In addition, since all these energy products are highly subsidized by the government, rapid increases in energy consumption is coupled with much higher expenses for a government that is already running a budget deficit. Reducing energy subsidies to save financial resources is very unpopular with the people since the country is predominantly poor. The current energy policies burden the government with an annual cost of 60 billion Egyptian pounds ($11 billion) from energy subsidies, an amount that is more than the government's health and education budgets combined. Thus, the government's current energy policies and infrastructure restrain it with two choices: remove energy subsidies and cause public unrest, or keep the subsidies and compromise the government's financial stability. Consequently, the government must restructure its energy policies and infrastructure to support the utilization of energy resources will never deplete, can serve the large growth in energy demand for the next 50 years and stabilize the government's energy budget.

Solar energy is Egypt's largest renewable resource; an area the size of Lake Nasser in Egypt can harness energy from the sun equivalent to the Middle East's whole oil production. The Egyptian solar energy resource can cover all of Egypt's current and future energy needs in addition to exporting over 35 billion Euros worth of solar electricity to the European continent by 2050 in an economically and technically feasible way that will meet a fifth of the continent's electricity demand. Prices from Egyptian solar energy electricity can become lower than both subsidized and unsubsidized fossil fuel based electricity if solar power plants are developed on a very large scale in the country. Thus, in order to achieve current and future energy and economic stability in Egypt, in addition to capitalizing on new opportunities that can provide a large part of the country's GDP, Egypt must develop a solar energy industry. An industry defined by high utilization of solar energy, local manufacturing of the technology, and research and development work in the field, must be developed in Egypt. This is an initiative that will create millions of jobs, generate billions of revenues and raise the living standards of the people. In short it can positively transform the country more strongly than anything it has seen in its modern history.

There are many solar technologies currently used around the world that Egypt can develop its new solar energy industry around. All of these technologies can be divided into PV or CSP technologies. PV technology is less favorable to build a solar energy industry around in Egypt than CSP technology. On large scale developments CSP technology can cost 70% less than PV technologies. In addition, it can also provide 24 hour on demand electricity by means of thermal storage. Whereas 24 hour on demand electricity is not economically feasible with PV since it requires an extremely high cost of large scale batteries. In addition, the very high temperatures of the Egyptian desert strongly reduce performance of PV systems and thus CSP technologies are a better fit because they are designed to operate at very high temperatures. Furthermore only a small share of PV technology can be manufactured locally and the technology requires very high capital, infrastructure and human training in order to enable an increase in the local manufacturing share. This makes CSP technologies more suitable for Egypt's industry since they have much higher local manufacturing shares and can further increase this share with less time and investments than what is required for PV. The two CSP technologies are currently most appropriate for the country are Fresnel technology and parabolic trough technology.

Fresnel technology has the least cost of solar electricity generation, the highest share of local manufacturing and is feasible to build and maintain in Egypt on a large scale. This makes it the best choice of technology to build an industry around in Egypt. Before large scale solar energy power plants can built in Egypt using Fresnel technology, a small pilot project should be constructed in partnership with one of the leading providers of Fresnel technology to raise Egyptian engineers' erection know-how of the technology to the state of the art level. After this small scale project the technology can be used to develop solar power plants all over the country or hybridize current fossil fuel power plants with a thermal input from the Fresnel solar collectors. Components required to construct solar power plants from this technology are readily manufactured in Egypt, whereas the parabolic trough design requires additional research and investments to develop its components in Egypt.

Although Fresnel technology is the best choice of technology for a solar energy industry in Egypt, since there is a solar power plant already being constructed using parabolic trough technology in Egypt, parabolic trough technology should not be altogether abandoned. Instead Egypt should focus the majority of its efforts on building large scale Fresnel solar power plants and build its solar industry around the Fresnel technology; in addition to devoting a smaller share of its efforts to gradually building on its experience with parabolic trough technology. This can be done in the form of using local materials to engineer the components required by the technology. No further parabolic trough power plants should be built unless the local components research efforts has produced results that allow for a higher local manufacturing share and a lower electricity cost than that of Fresnel technology.

Chapter 7: Case Study on Egypt's Experience with Parabolic Trough Technology

Figure 45: The author pictured at the construction site of the parabolic trough solar power plant in Kuraymat, Egypt, during his visit on March 26th 2009.

We have seen that Parabolic Trough technology is the oldest and most developed CSP technology. What you might find surprising, is that the first parabolic trough solar collector was built in Egypt in 1912.

This section presents a case study about Egypt's experience with constructing parabolic trough collectors. We will start with from the early experience of 1912 where the heat generated by the parabolic troughs was used to drive a steam engine which in turn provided power for pumps that used water from the Nile to irrigate nearby agricultural fields. Then we will proceed to the 2001 experience where heat from parabolic trough collectors was used to supply steam for a pharmaceutical factory. Finally we will visit the most current experience of 2008, where the heat generated by currently under construction parabolic troughs will be used to produce electricity in a conventional generator for the national grid.

The goal of this case study is to describe how the know-how required for constructing power projects with parabolic trough technology was transferred to Egypt. To achieve this we will present the successful and successful attempts that have been made in Egypt. In all these attempts the various parties that were involved in this process, the resources that were required to complete the project and the size of the project itself are discussed. To complete this case study the author visited the construction site of the Integrated Solar Combined Cycle (ISCC) power plant (which uses parabolic trough technology) in Kuraymat, Egypt on March 26th 2009, where he conducted interviews with the site's project manager, head engineers and various technicians involved in the project. In addition, the author's information on this project comes from other conversations with the CEO of the project's construction contractor, the managing director of the project's technology provider, and the chairman of the entity that owns the power plant. Furthermore, the author served as an advisor to the project's construction contractor during the negotiations of the final contract with the technology provider and the client.

7.1 Egypt's Early Experience with Parabolic Trough Technology (1912)

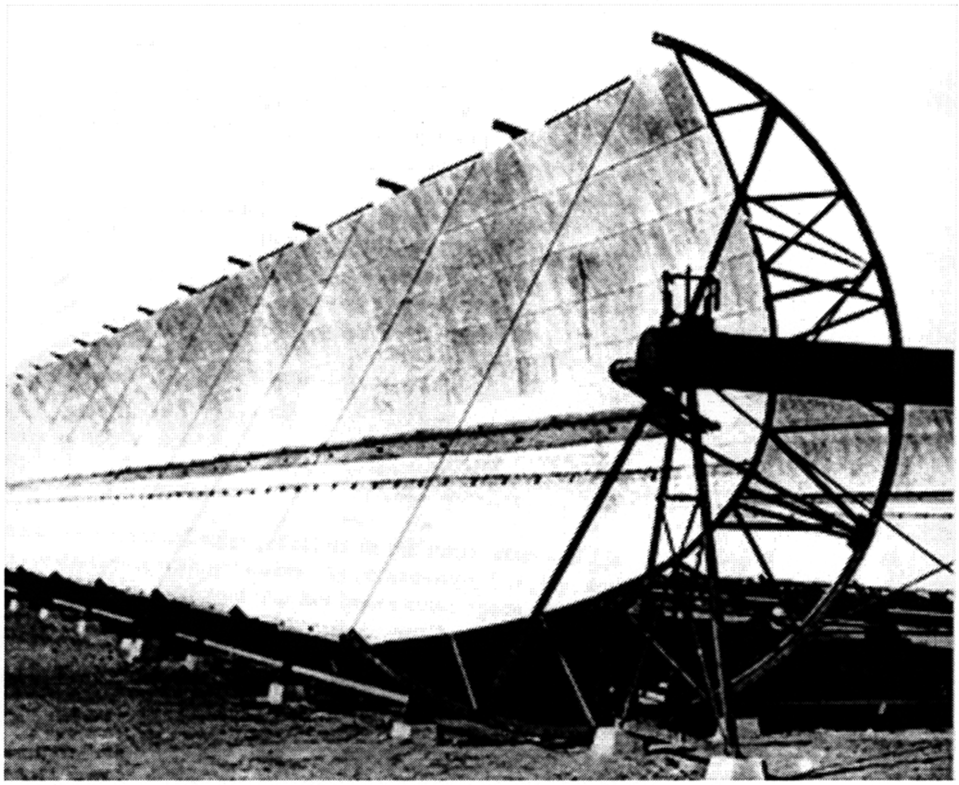

Figure 46: One of the Parabolic Troughs built in 1912 in Cairo, Egypt

Source: Solar Haven

The world's first solar thermal power station based on the parabolic trough design was built in Cairo's district of Maadi in 1912. The troughs were built by a German-American engineer, Frank Shuman who pioneered the parabolic trough design in Philadelphia. Shuman came to Egypt to experiment with the technology under an invitation from Lord Horatio Herbert Kitchener, a British war hero who became England's consul-general to Egypt in 1911 under the British occupation of the country. Lord Kitchener had heard of Shuman's new device and thought it would be ideal for irrigating the Nile Valley. Shuman's design was based on 5 parabolic troughs, each of them 13 feet in width and 204 feet in length. The basic CSP plant was used to power a 55 horse power engine that pumped 6,000 gallons of water per minute from the Nile River to adjacent cotton fields.

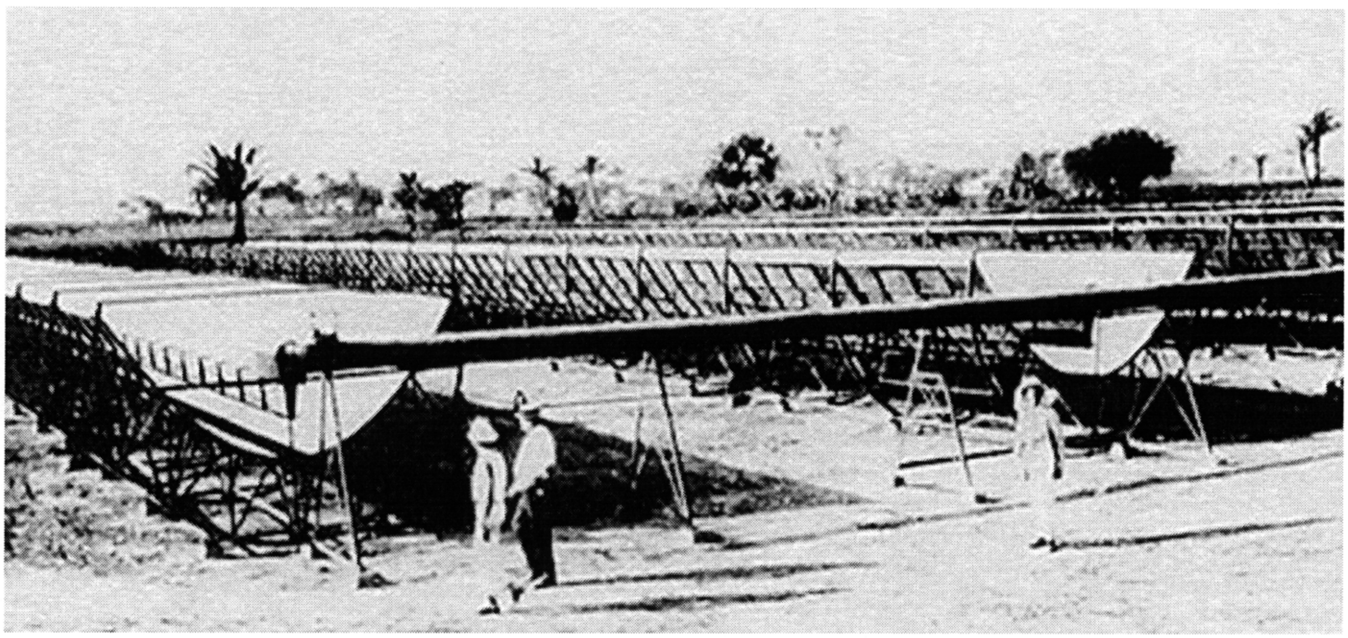

Figure 47: A view of the solar thermal station in Maadi

Source: Solar Haven

At the time, Shuman's work was ground breaking and received a lot of attention. It also resulted in an invitation to Shuman from the German government to build more of these solar stations in Germany's African colonies under a $200,000 financing scheme from the German government. Shuman envisioned building parabolic trough collectors across 52,447 million square meters in the Sahara desert to produce 201 GW of energy from solar power, an amount equivalent to the world's entire amount of coal mined in 1909. Unfortunately, the outbreak of World War I sent all the foreign engineers working on this project in Egypt back to their home countries to work on war related tasks, while the German government forgot about solar energy all together and shifted its attention to the development of internal combustion engines for use in cars and airplanes, and Shuman died before the war ended. All these factors in addition to the discovery of cheap oil stopped completely the development of solar energy in Egypt and the world. It was not until the 1980's when the parabolic trough solar power plants of California's Mojave Desert were built under financial incentives from the local government that parabolic trough technology was revisited. In the next section we will explore Egypt's second experiences with parabolic trough technology.

7.2 Egypt's Experience with Parabolic Trough technology for Industrial Heat Processes (IHP) 2001

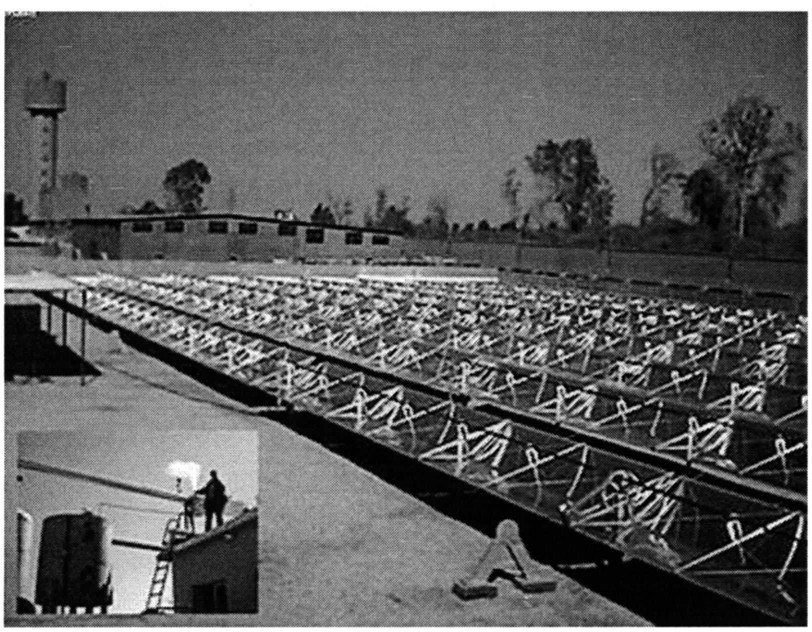

Figure 48: The El-Nasr parabolic trough field Source: Solarpaces

In 1999 the New and Renewable Energy Authority (NREA), a division of the Egyptian Ministry of Electricity issued an invitation for bids for the construction of the first pilot parabolic trough field since the 1912 demonstration. The heat produced from the parabolic trough field was used to supply saturated steam for a manufacturing process in a pharmaceutical factory called El-Nar. Before the construction of the parabolic trough field the factory had been using heavy oil to generate saturated steam for its industrial processes.

The motivation of the project was the size of the Industrial Heat Processes Market in Egypt. In 1995, NREA in collaboration with Fitchner Solar, a German consulting firm, calculated that fuel consumption used to generate heat for industrial processes in Egyptian factories was 136,000 barrels of oil per day, with a value of over $1 billion per year. In 2011 fuel consumption for IHP is expected to be 235,280 barrels of oil per day, a 73% increase over the 1995 figures. Consequently if the sun's power could be harnessed in producing heat for industrial processes it would save a lot of valuable fuel.

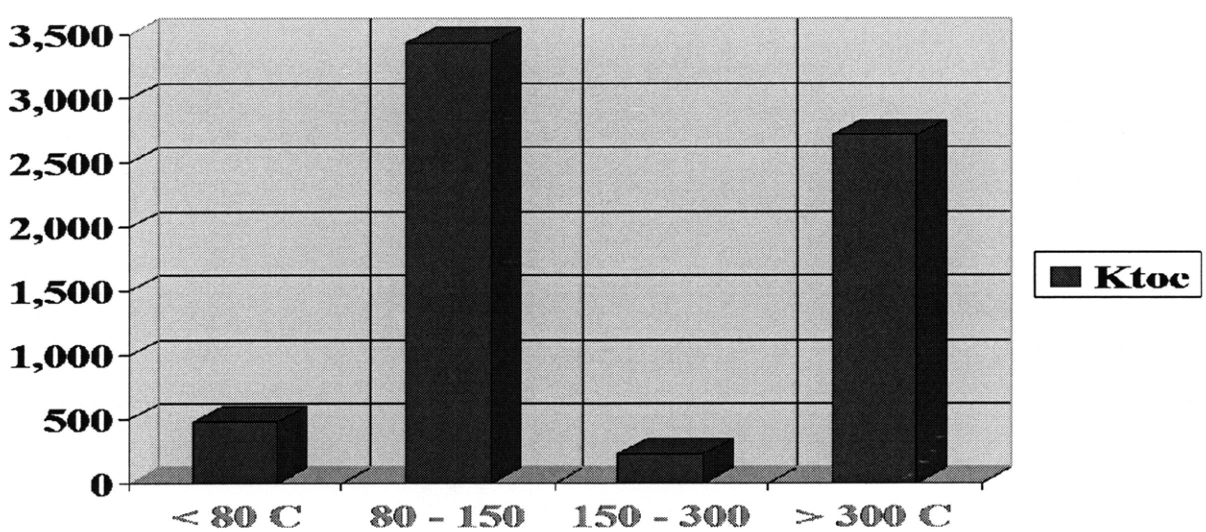

Figure 49: NREA and Fitchner study showing heat consumption in kilo tons of oil equivalent (ktoe) for industrial heat processes in 1995 and required temperature ranges Source: NREA

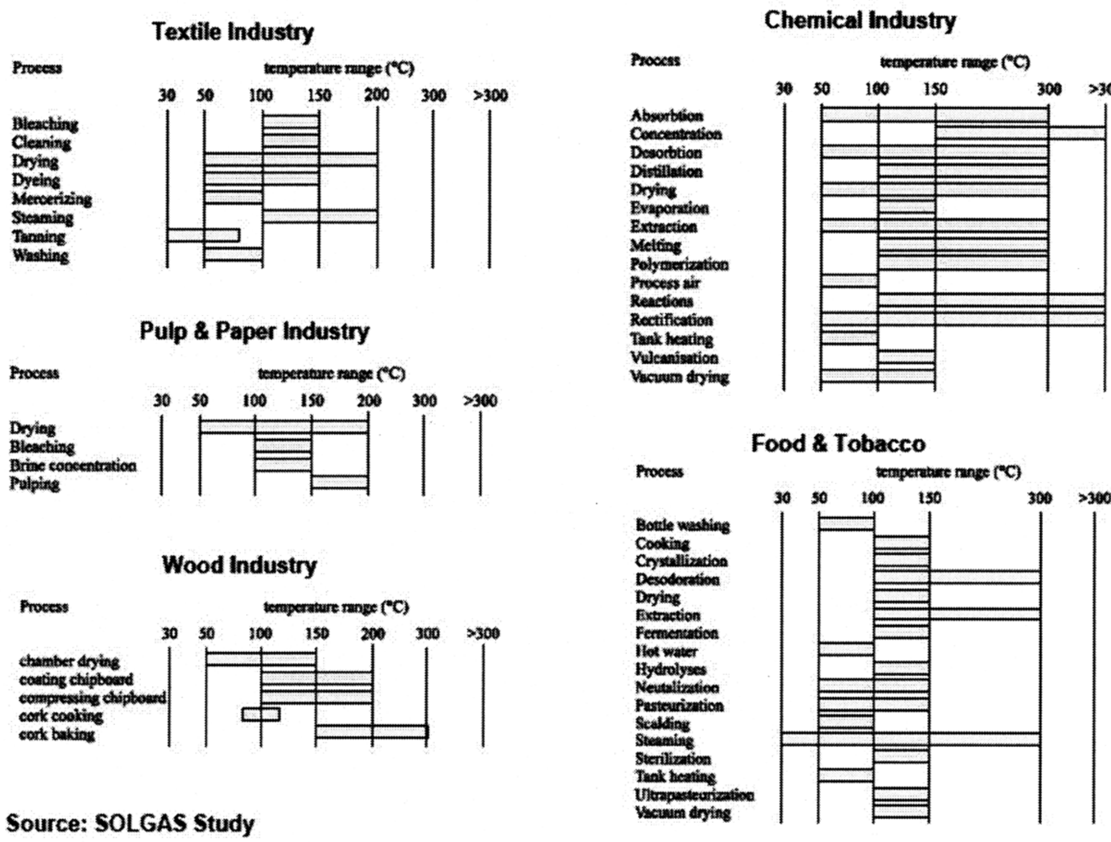

Figure 50: IHP temperature requirements for different industries in Egypt

Source: SOLGAS study

The African Development Fund provided a $1.1 million grant to finance NREA's project. The winner of the bidding round was announced in May 2000, an Egyptian company called Lotus Technologies. The company is a construction contractor that had no previous experience with solar energy projects. When NREA officials were asked about why Lotus Technologies was selected, they mentioned that it was because the company had a partnership with an American company specialized in designing solar projects of this kind. However this partnership had fallen out after the project was awarded to Lotus Technologies and Lotus implemented the project by itself.

The El Nasr Project involved the creation of saturated steam at a pressure of 8 bar and a temperature of 175 degrees Celsius by means of the parabolic trough field. The parabolic trough field was compromised of 144 parabolic trough collectors covering a total area of 1,900 meters squared. Construction of the solar field began in August 2001.

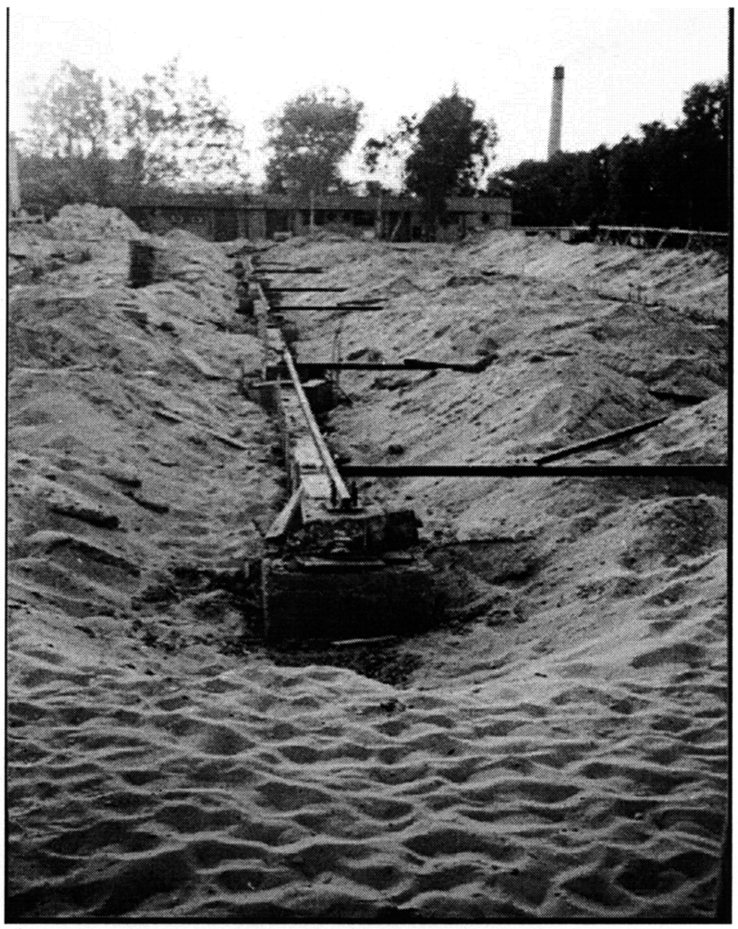

Figure 51: Construction of the ground foundation for the parabolic trough collectors

Source: Lotus Technologies

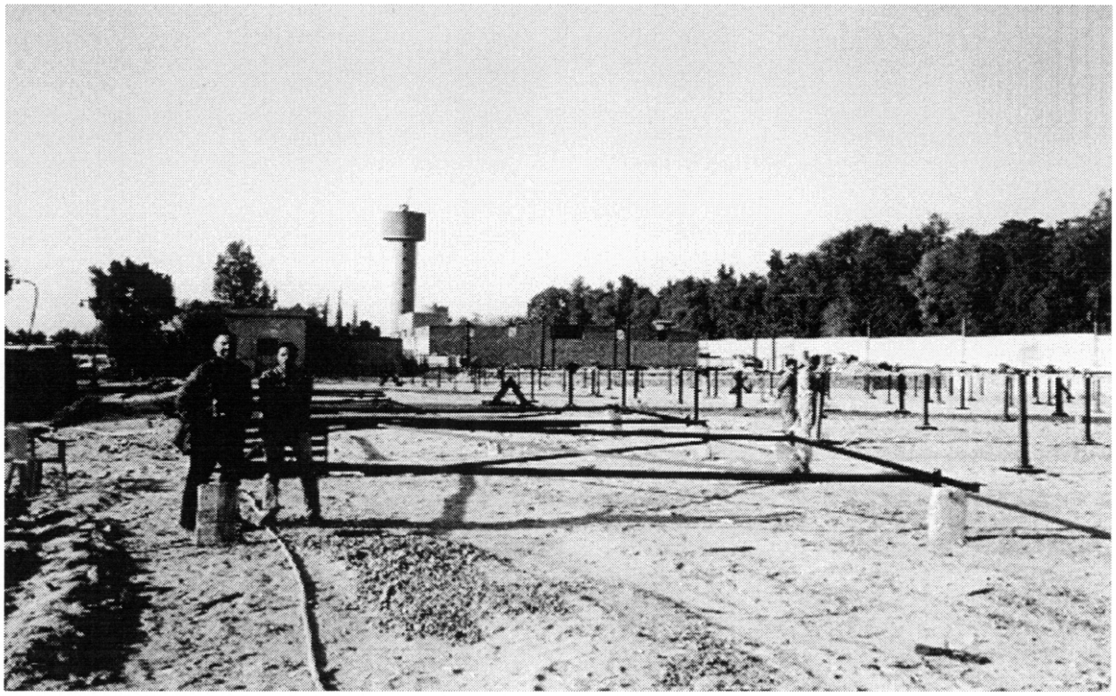

Figure 52: Rest of Civil Works construction Source: Lotus Technologies

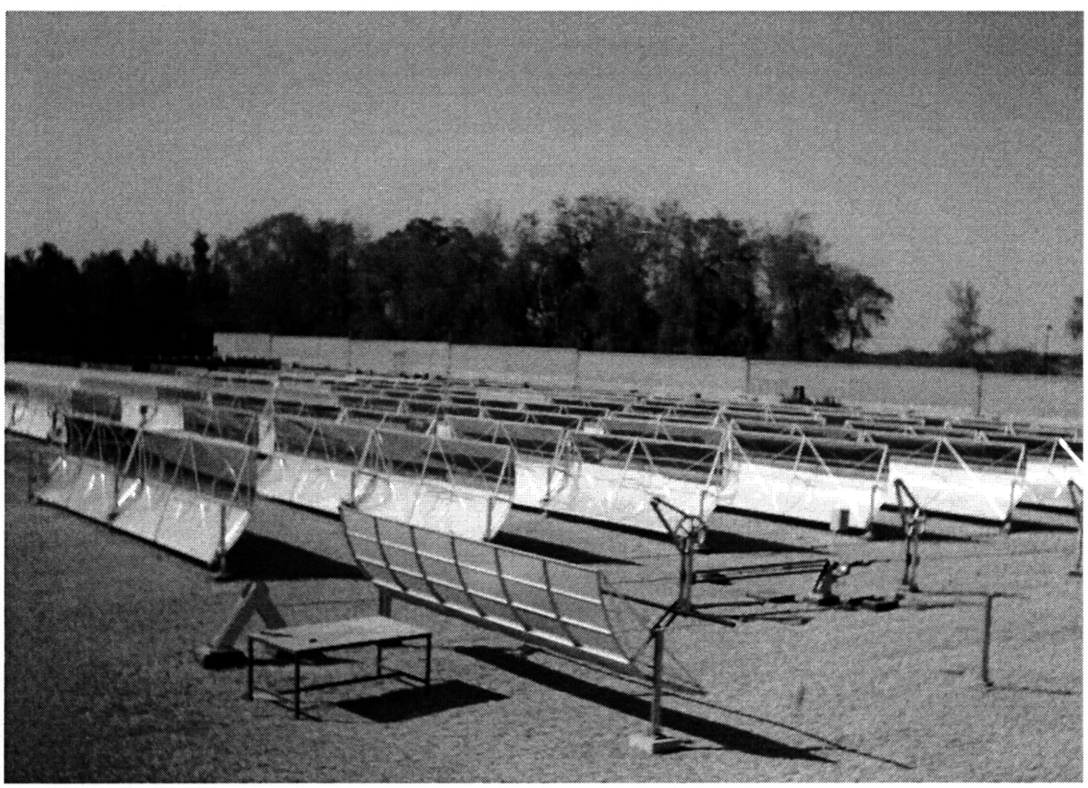

Figure 53: Collector Assembly Source: Lotus Technologies

When construction was complete and the parabolic trough field was commissioned in May 2004 the steam production rate was lower than the 850 kg per hour required by NREA in the contract. After investigating the problem, Lotus Technologies tried making various modifications to the plant and a rehabilitation program was completed in 2005 which improved performance. However, shortly after the rehabilitation program was complete, steam production from the parabolic trough collectors began to fall beyond the 5% per year degradation that Lotus Technologies had guaranteed as a maximum annual degradation in its contract with NREA . Lotus Technologies made some more investigations and concluded that the aggressive air environment in the factory accelerated the deterioration of the reflectance and absorption properties of the parabolic troughs which as a result reduced the saturated steam output. Periodic rehabilitation has been scheduled by Lotus Technologies to combat this degradation and NREA was not happy with the results of the project. Plant enlargement for additional parabolic trough collectors to increase the steam output of the plant failed to raise the necessary funding.

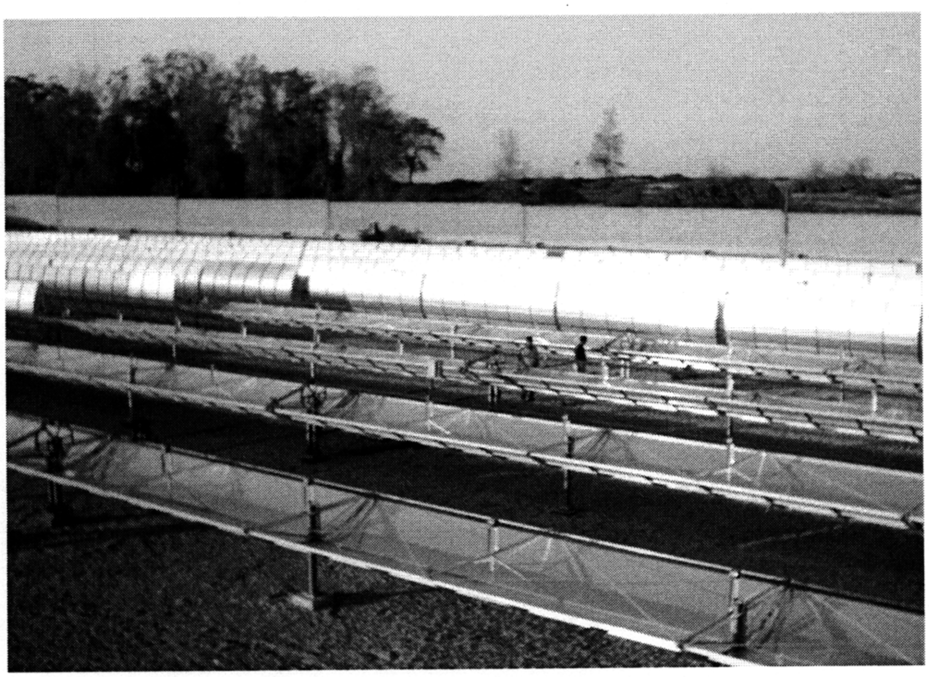

Figure 54: Parabolic trough field after construction Source: Lotus Technologies

The fact that Lotus Technologies did not have any previous experience with parabolic trough technology and had lost its partnership with its experienced American technology provider before construction began; was what was behind the failure of this project. Lotus Technologies did not have the previous know-how to design and construct successful parabolic trough projects nor did it have a partner that could transfer this know how to it. Consequently, Lotus Technologies was not able to achieve the results set in the contract agreement.

Some of the issues that Lotus Technologies could not have implemented well in the construction process and might have led to the decreased performance of the plant include: not assembling the parabolic trough structure in the accurate parabolic geometry required, not fabricating steel structure with high accuracies required for parabolic troughs and not developing the ground foundation for the parabolic trough collectors with the high accuracies required. In the next section we will discuss a successful transfer of know-how to Egypt for parabolic trough technology.

7.3 Egypt's Successful Experience with Know-How Transfer of Parabolic Trough Technology for Electricity Generation (2008)

Figure 55: Construction of the Kuraymat parabolic trough solar power plant

Since the 1990's the Egyptian ministry of electricity and NREA have been planning for a solar power plant in Egypt. After conducting feasibility studies for this project, raising the required capital and preparing the bidding documents, a request for proposals to construct the first solar power plant in Egypt and the Middle East was issued by NREA on behalf of the ministry of electricity in 2006. The location for the project was chosen to be in Kuraymat, Egypt, a site around 90 km south of Cairo. This site was selected because of the 2400 kWh per meter squared per year of solar DNI it receives, its proximity to natural gas pipelines, sources of water and a connection to the power grid. In addition the location is uninhabited, and the ground terrain is flat desert.

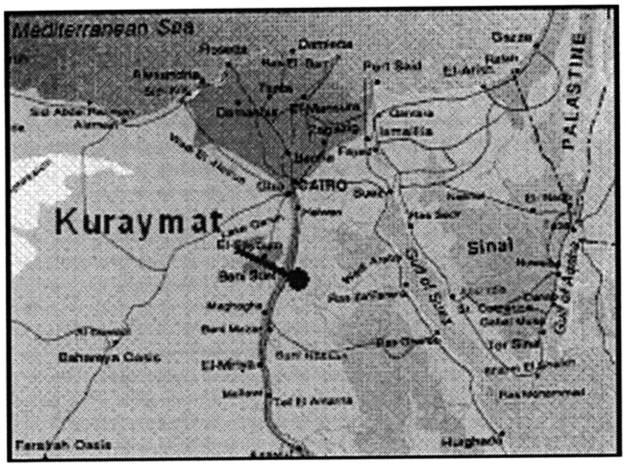

Figure 56: Location of Kuraymat on the Egyptian map Source: Solarpaces

The request for proposals was structured so that NREA would award three different contracts to the respective bid winners. The first was an Engineering Procurement & Construction (EPC) contract for the solar island of the power plant, the second was an EPC contract for the combined cycle of the power plant, and the third was a two year Operation & Maintenance (O&M) contract for the power plant. For the same reasons mentioned before, our attention is focused on the solar island component of the power plant.

Four different companies purchased the bidding documents for the solar power plant: Abengoa Solar, a leading Spanish company in solar energy projects; Iberdola, another leading solar energy Spanish company, Orascom Construction Industries (OCI) an Egyptian construction contractor with no previous experience in solar energy projects, and Hassan Allam Sons, another Egyptian construction contractor with no previous experience in solar energy projects. Hassan Allam sons was the only company out of the four that did not submit a bid, after all bids have been submitted, Orascom was awarded the EPC and O&M contract for the solar island of the power plant. These contracts were awarded to Orascom because it submitted the lowest bid price out of all three companies.

Figure 57: Orascom is the largest construction company in Egypt with annual revenues exceeding $3 billion Source: Orascom

According to the EPC contract awarded to Orascom, the company was responsible for the complete turn-key construction of the solar island in addition to providing O&M services for two years after the construction is complete. Throughout and after the bidding process, Orascom had a subcontract agreement with Flagol, a leading German company in the construction of parabolic trough solar islands. Under the agreement, Flagsol was to provide all detailed engineering, design and components supply for the construction of the solar island, In addition to providing O&M services for the power plant for two years and training a group of 20 Egyptian engineers to be able to run the solar power plant independently after the two year term is over. In addition, Orascom's scope of work in the agreement with Flagsol included all civil works, and erection for the solar island. Moreover, Flagsol will also provide supervision throughout the assembly and erection process of the solar island.

According to the contract, the solar island would supply thermal power to the steam turbine of the 140 MW combined cycle power bloc of the power plant. The solar island would generate a capacity of 65 MW of thermal heat that is equivalent to an electrical power share of 20 MW generated by the steam turbine. This means that the power plant will be run in hybrid between solar and fossil fuel resources. The solar island would contribute about 20 MW of the electrical power output and fossil fuel resources would contribute the rest of the 140MW power output. This type of power plant is called an Integrated Solar Combined Cycle (ISCC). Thus instead of storing thermal energy captured from the sun for use at night, the power plant will by operating on 100% fossil fuel mode at night.

The solar field has as size of 130,800 m² and consists of parabolic troughs carrying a total of 53,760 mirrors. Financing for the $327.57 million construction cost of the solar power plant was provided through a $50 million grant from the Global Environment Facility division of the world bank, a $113 million loan from the National Bank of Egypt, and a $89.5 million loan from the International Bank for Reconstruction and Development. Electricity generated from the power plant after its completion in 2010 will be supplied to the national grid.

As we will see in the following sections, the subcontractor agreement between Orascom and Flagsol allowed for the transfer of know-how and expertise in constructing and operating solar power plants based on the parabolic trough technology to Egypt. As opposed to the case of the El-Nasr solar field discussed in the previous section, where there was no experienced technology provider to generate this transfer of know-how. Consequently, Orascom has developed certain skills and understanding of parabolic trough design from working with Flagsol on the Kuraymat project that will allow it to build large scale solar power plants in the future in Egypt at less cost and less time. In the next section, the know-how that was transferred to Egypt as a result of this project is discussed.

7.3.1 Ground Foundation Construction Know-How Transfer

In order to be able to focus sunlight to very high concentrations, parabolic trough collectors must be erected and assembled very accurately to create the required geometry. This leaves very little room for margins of error, which makes this task very hard to accomplish when high accuracy is required for the civil structure of collectors that are hundreds of meters long. It is thus very unlikely for a contractor with no experience in this to be able to complete this project by itself while maintaining the high accuracies required.

Flagsol's supervision of the construction process helped Orascom engineers and technicians build the ground civil structure of the collectors with the high accuracy required in addition to helping them develop new tools and methods to measure accuracy and assess the success of the installation. After the first few months of this exercise, Flagsol's supervising engineers were impressed with that pace that the Egyptian engineers were moving with. Consequently, cost reductions can be achieved in the next solar project as a result of the faster pace the project will move with and the higher efficiency of using materials.


Figure 58: The ground structure of parabolic trough collectors constructed at the Kuraymat site

7.3.2 Collector Steel Structure Construction Know-How Transfer

As with the ground civil structure discussed above the steel structure carrying the collector has to be assembled with very high accuracy and the steel bars themselves also have to be manufactured with the same high accuracy. The Egyptian National Steel Fabrication company (NSF) was subcontracted by Orascom to supply the 3,200 tons of steel required to build the support structure of the collectors.

Schlaich Bergermann und Partner (SBP) is a German structural consulting engineering company that has designed the steel structure for many of the world's CSP power plants. SBP was also subcontracted by Flagsol to design the steel structure for the Kuraymat solar power plant.
In order to meet the precision required in SBP's steel structure design, NSF had to invest in new equipment such as state of the art CNC machines in order to fabricate steel with the required

accuracy. In addition, SBP and Flagsol engineers were present on site to ensure the careful assembly of the collector steel structure by Orascom and NSF technicians.

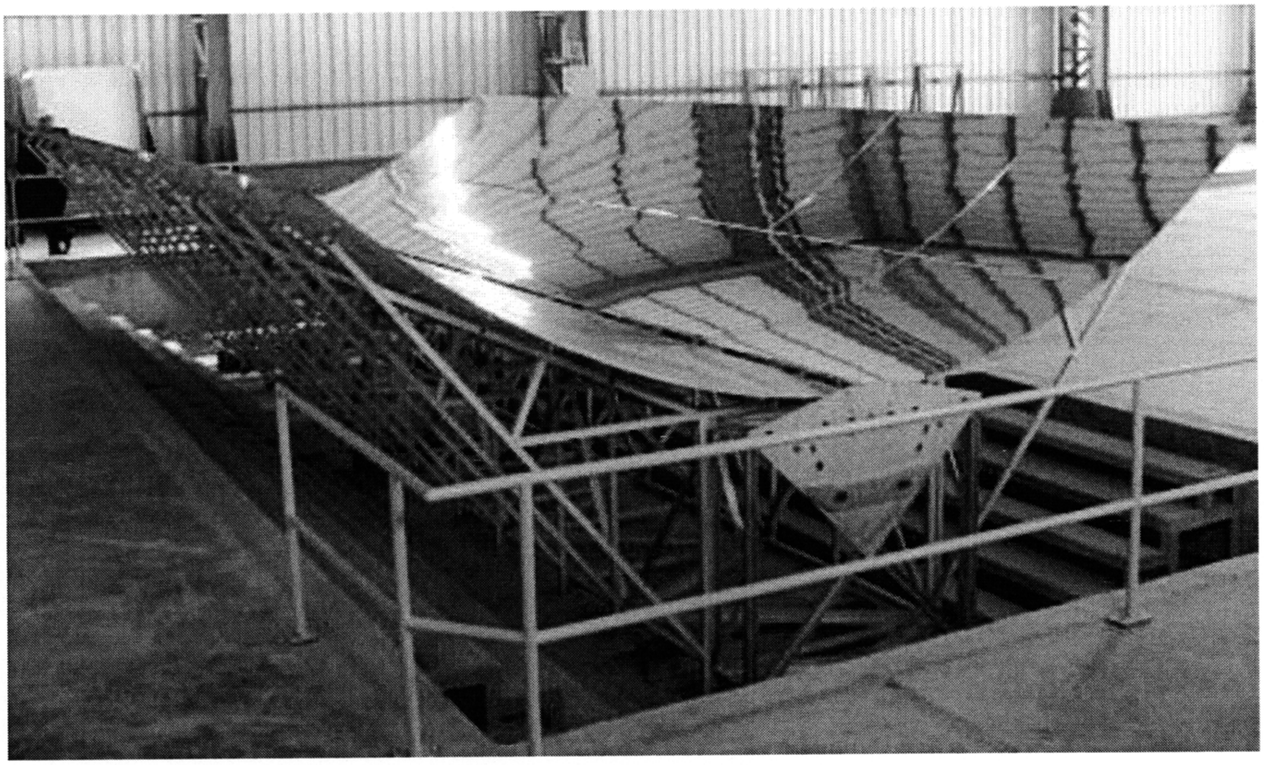

Figure 59: Collector steel structure after assembly by Orascom and NSF is seen in this image. Note that the mirrors used as a reflective surface have already been place on the steel structure in this image

As a result of this experience, state of the art technology is now available in Egypt to fabricate high precision steel structure for parabolic trough solar collectors. In addition to the availability of technicians with the know-how of high accuracy assembly of the steel structure required for the collectors.

In the final stages of the collector assembly, the collector is tested using advanced photogrammetric geometry techniques and equipment introduced to Orascom by Flagsol engineers to ensure that the collector has the right geometry that would generate the required thermal output (this is an extremely effective method of quality control that ensures quality before erection of the collector as opposed to the El-Nar project where quality control efforts were made to try and improve performance after the collectors were erected in site.)

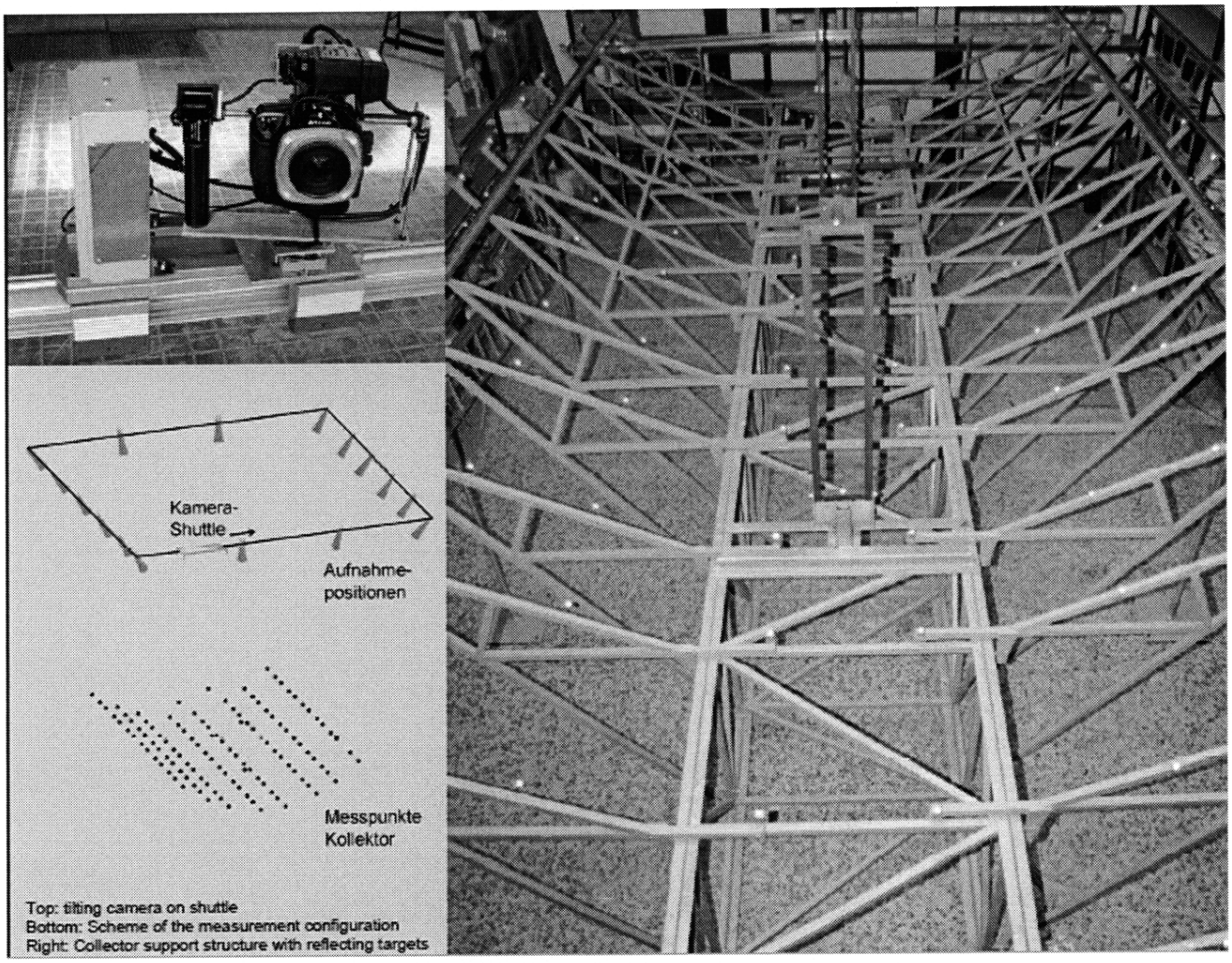

Figure 60: Setup for Photogrammetric quality control measurements Source: German DLR

Consequently, due to the strong correlation between the geometry of the collectors and their annual efficiency quality control procedures are applied before installation in order to reach the performance set in the design. With the collector frame placed in the measurement area, retro-reflecting targets are applied on attachment points were the mirrors and receivers are supposed to be placed. The image evaluation results are used to identify deviations from the design requirements for adjustment in the quality control process.

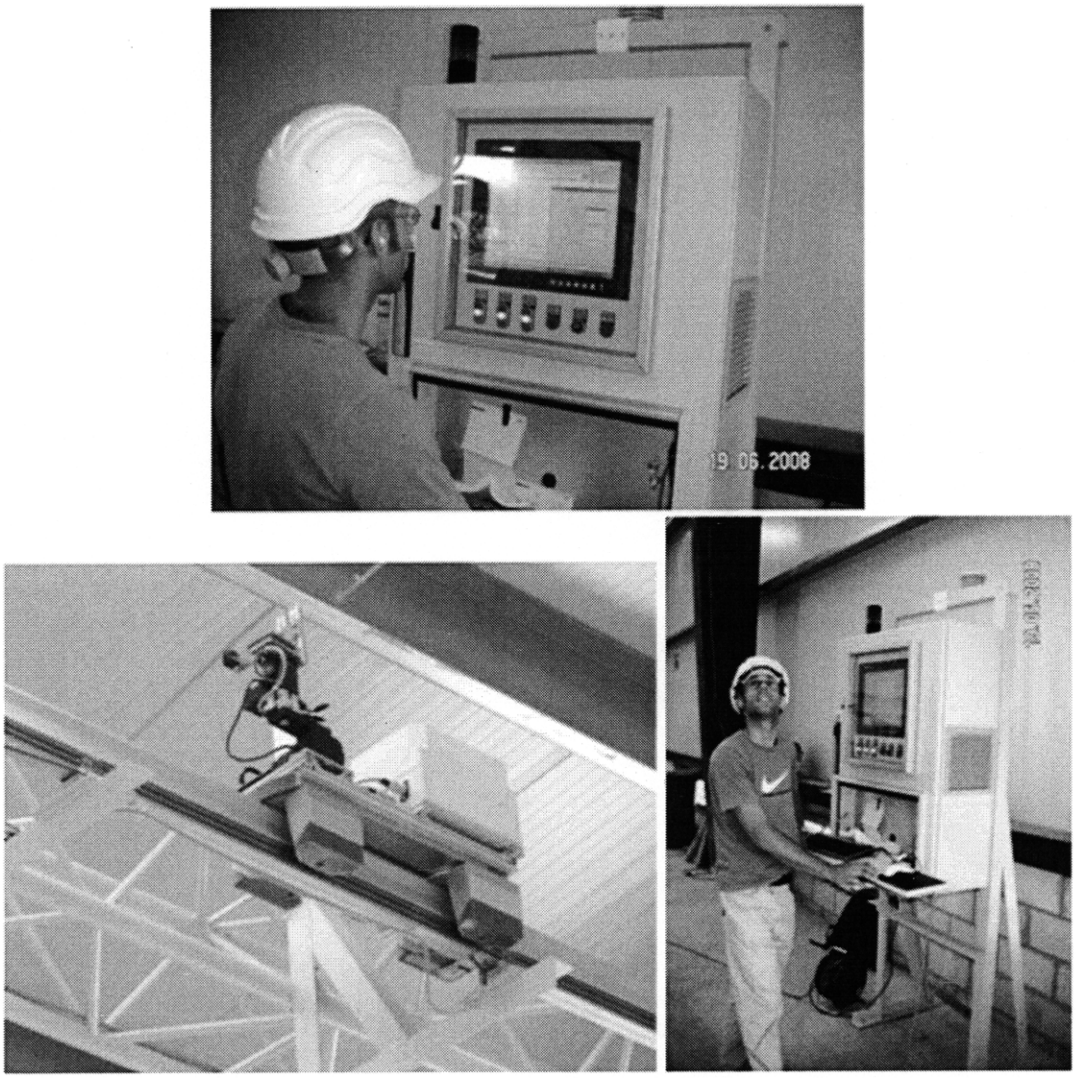

Figure 61: A technician conducting Photogrammetric measurements on a collector

Source: CSP Services

If the collector meets the required geometry criteria, the reflective surface is placed on top of the collector and it is transported from the assembly area to the erection area to be placed on its ground civil structure as seen in the figure below. The last stage in collector erection is attaching the absorber tube to its support structure on top of the collector surface.

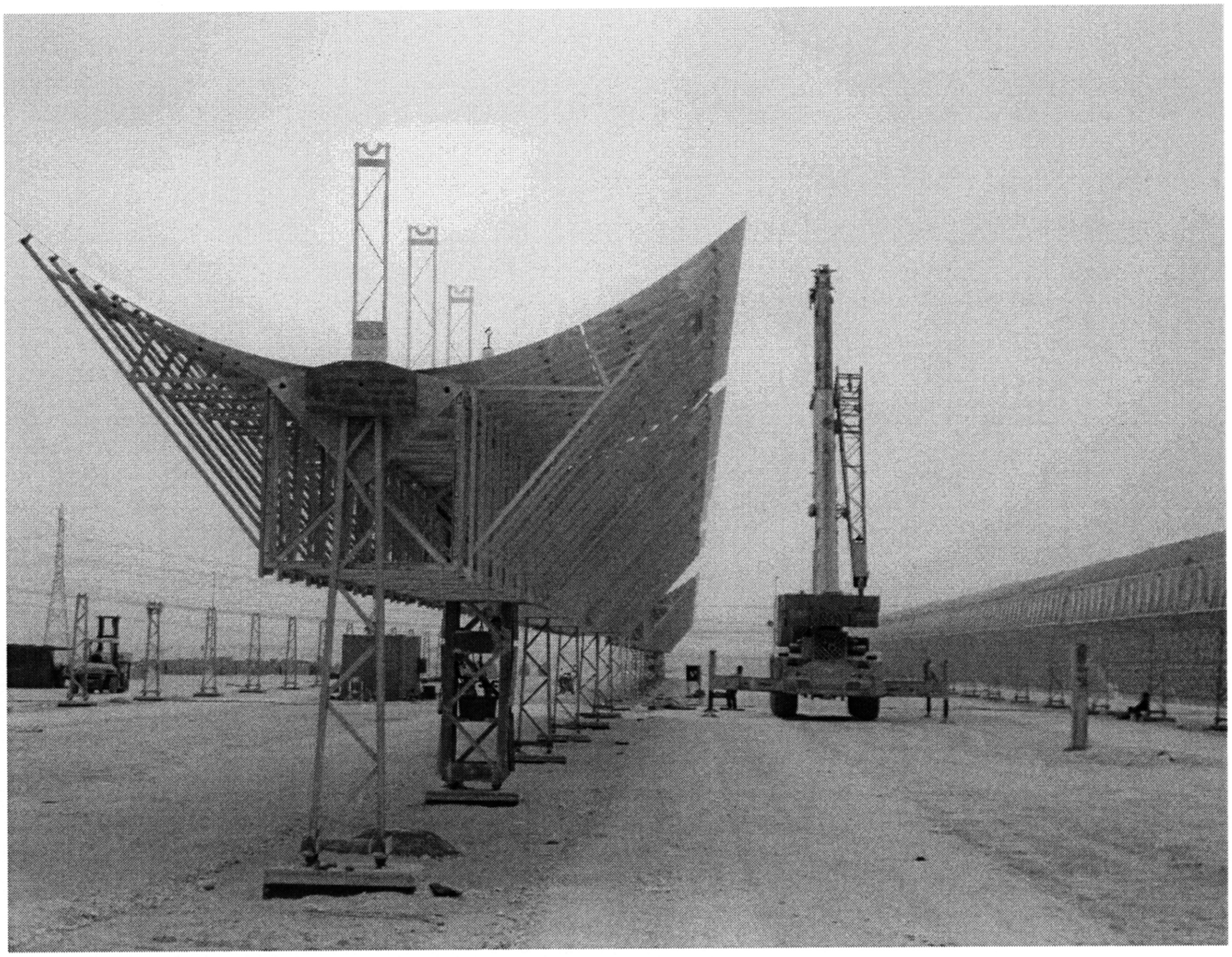

Figure 62: Erection of the parabolic trough collector on its ground civil structure. Note that the absorber tube has not been erected yet at the time this picture was taken in March 2009. The absorber tube support structure is seen in a vertical position on the surface of the collector

In conclusion, we have seen how critical know-how has been transferred from the European companies to Egyptian engineers in the multiple areas discussed above that are critical in developing parabolic trough solar fields. The lack of this know-how was the biggest factor behind the weak performance of the parabolic trough field in the El-Nasr Project discussed in the previous section.

Even though the power plant is still under construction, we know that in the same way that the above know-how has been transferred to Egyptian companies, know-how required to complete all outstanding tasks in the construction of the solar power plant will also be transferred to the Egyptian companies because of the structure of the contract agreement and scope of work between Orascom and Flagsol.

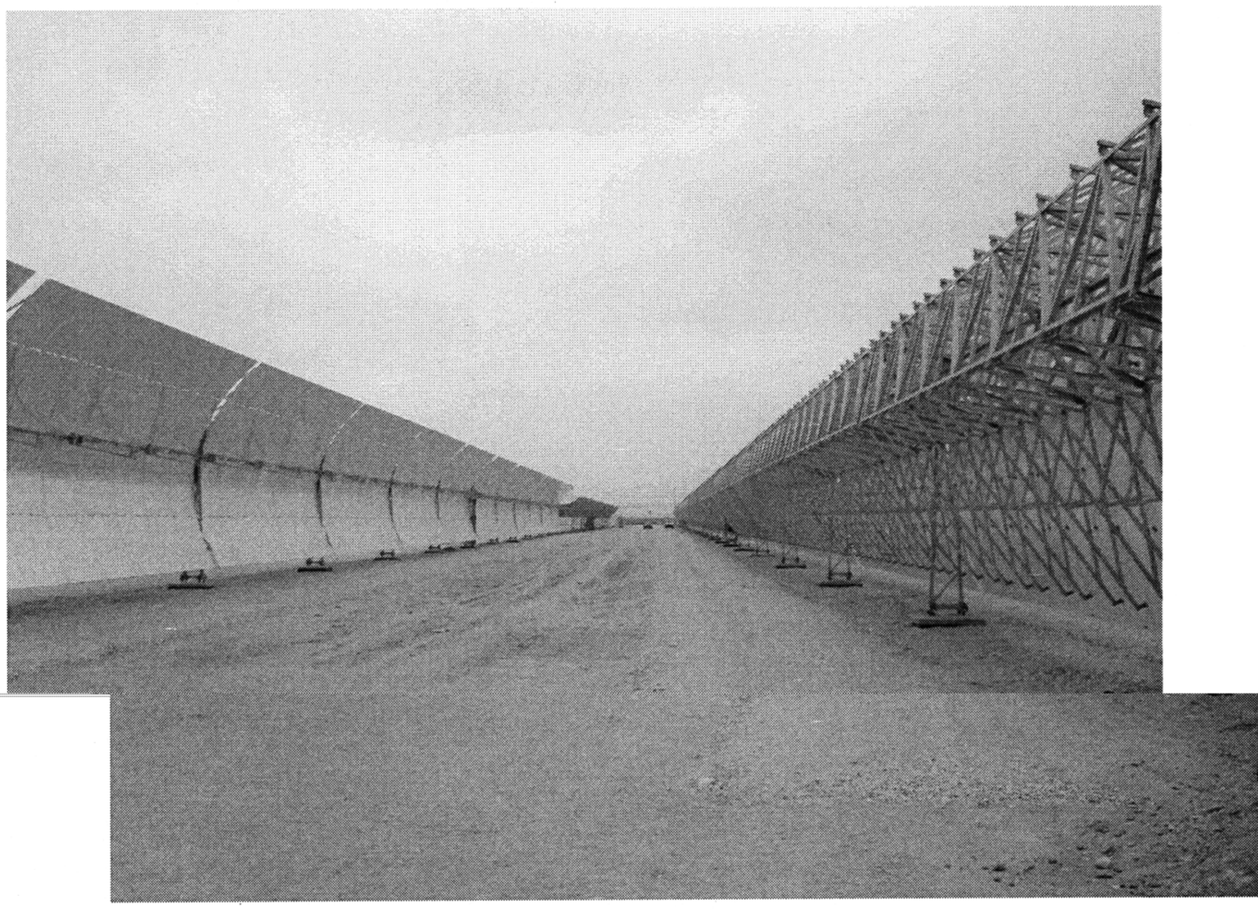

Figure 63: Rows of parabolic trough collectors constructed at the Kuraymat site

Finally, the absorber tubes used in this project were supplied by Schott solar and the mirrors used as the reflective material were supplied by Flabeg, both of which are German companies that are the leaders in their field. In addition the heat transfer fluid was Therminol VP-1 supplied by

Solutia, an American company that is also the leader in its field. All of these suppliers were chosen by Flagsol since it was in its scope of work in the subcontract agreement with Orascom to procure all the components required for the parabolic trough collectors excluding civil works.

As a result of the successful know how transfer to Egypt that came about after working with top technology providers in the parabolic trough technology industry to construct the Kuraymat solar field; Egypt can now build large scale parabolic trough solar islands to harness the power of the sun for applications such as electricity generation, heat generation for industrial processes and water desalination by thermal processes.

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